

Ionospheric oscillations caused by geomagnetic Pi2 pulsations and their observations by multipoint continuous Doppler sounding; first results

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Abstract

In 2004, we started operating a continuous Doppler sounding system to investigate ionospheric signatures of infrasonic, short period acoustic gravity waves and geomagnetic pulsations. Since January 2007, four stable 3.59 MHz transmitters have been in operation in the western part of the Czech Republic. Multipoint measurements enable us to investigate horizontal propagation of waves and disturbances in the ionosphere and to estimate horizontal distances over which these waves (disturbances) are correlated.

We focus on cross-correlations between Doppler shift records and irregular night-time Pi2 pulsations of the geomagnetic field measured on the ground at the observatory of Budkov. These pulsations have periods $\sim 1\text{--}3$ min and occur simultaneously (within the precision of the measurements) on all Doppler sounding signals. The sounding signals (Doppler records) are usually best correlated with the variations of the horizontal component of the geomagnetic field. Generally, a good correlation with the variations of the magnetic field amplitude is also observed. The observed geomagnetic pulsations were predominantly left-handed with an elliptical or nearly linear polarization. In one case, we have also observed right-handed pulsations. Our observations show that the time/phase shifts between geomagnetic field components and Doppler shift signals can change from case to case.

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1. Introduction

Continuous Doppler sounding by high frequency (HF) radio waves is often used to study perturbations of the ionosphere induced by geomagnetic fluctuations and acoustic gravity waves (AGW). The principle of measurement is based on the fact that the ionospheric plasma causes a refraction of radio waves owing to the gradients of plasma density. The refraction leads to total reflection at vertical incidence for waves of frequencies lower than the maximum plasma frequency in the ionosphere. At oblique incidence reflection occurs up to higher frequencies, depending

on the angle of incidence. Reflected waves experience a Doppler shift when the signal phase path in the ionosphere changes with time (Davis and Baker, 1966). Since the plasma density gradients in the vertical direction are usually much larger than the horizontal gradients, the main contribution to the change of signal phase path comes from vertical movement of the ionospheric plasma forming the reflection layer. Such a vertical movement can be caused, for example, by $\mathbf{E} \times \mathbf{B}$ drift induced by the alternating electric field of an incident magneto-hydrodynamic wave (Rishbeth and Garriott, 1964). A detailed theory was developed by Sutcliffe and Poole (1989) who showed that the phase path can also change due to magnetic field variations and compression/rarefaction of the plasma by the wave fields. The incident magneto-hydrodynamic waves are

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often called ultra low frequency (ULF) waves according to the frequency band in which they occur.

The ULF waves incident on Earth's ionosphere are produced by different processes in the Earth's magnetosphere and solar wind (see for example an introductory review by McPherron (2005) and references therein). The ULF waves are usually classified according to their waveforms and periods (Jacobs et al., 1964). Waves with quasi-sinusoidal form are called pulsations continuous (Pc), those with irregular waveforms are called pulsations irregular (Pi). In the present paper, we will focus on night-time Pi2 pulsations of periods ~ 50 – 180 s. A phenomenological model linking flow bursts in the magnetotail at distances between 8 and 15 Earth radii, the substorm current wedge, and Pi2 magnetic pulsations was proposed by Kepko et al. (2001).

It should be noted that the ionosphere has a significant effect on ULF waves seen at the ground. Hughes (1974) showed that the horizontal polarization of the ULF wave at the ground is rotated 90° with respect to the polarization of the wave incident on the ionosphere. The reason is that the magnetic perturbations seen on the ground are electromagnetic waves radiated from currents induced in the ionosphere by incident ULF waves. Hughes and Southwood (1976a, b) studied the attenuation of a ULF signal by the ionosphere and came to the conclusion that fine horizontal structures in the magnetospheric signal (with horizontal scale less than ~ 50 km) are not detectable on the ground because the ionosphere has a smoothing, space averaging effect on the incident wave structure.

A comparison of ionospheric oscillation with magnetic pulsations on the ground has recently been performed by several authors. Menk (1992) presented a statistical comparison of the north–south component of ground magnetic pulsations and Doppler data with the predictions of the Sutcliffe and Poole model (1989, 1990) which assumes transverse Alfvén waves incident on the ionosphere. He found relatively good agreement between daytime observations (Pc3-4 pulsations) and model predictions, but less satisfactory agreement for night-time Pi2 pulsations and argued that fast and coupled wave modes may also be responsible for these pulsations. Marshall and Menk (1999) found that simultaneous Doppler and magnetic oscillations exhibit highest correlation when the radio waves reflect near the F layer peak. They also reported a surprising phase shift between oscillations in the ionosphere and geomagnetic pulsations on the ground for all frequencies below the local field line resonance frequency. At high latitudes, the correlations between Doppler records and magnetic fluctuations were investigated by Wright et al. (1997). They associated the pulsations with field line resonances and concluded that the vertical component of the $\mathbf{E} \times \mathbf{B}$ drift is the dominant mechanism in the ionosphere that produces the Doppler shift. Waters et al. (2007) presented a combined experimental and modeling study of the Doppler shift of radio waves reflected from the ionosphere caused by the interaction of ULF wave energy with ionospheric plasma. They used the Sutcliffe

and Poole model (1989, 1990) with parameters adjusted to particular ULF wave events and identified the $\mathbf{E} \times \mathbf{B}$ drift as the dominant mechanism for changing the radio frequency. They also discussed the spatial averaging effect of the ionosphere on the ground observations.

Here, we present first results of a correlation study between Doppler shift measurements and magnetic pulsations in the Czech Republic. We show the time/phase shifts between oscillations in the ionosphere and geomagnetic fluctuations vary from case to case. We also present spectral analysis of the signals and the polarization of geomagnetic fluctuations at the ground. We use data from geomagnetic observatories and a multipoint Doppler sounding system. This system was primarily designed to investigate propagation of acoustic gravity waves and infrasonic waves in the ionosphere; the velocity of propagation being estimated from time delays between different observation points. However, the ionospheric oscillations caused by ULF waves occur simultaneously – within the precision of measurements – in all sounding signals. Section 2 describes an arrangement of the measurement and observation facilities. Examples of data are given in Section 3. Data analysis and results are presented in Section 4 and finally, a short summary is given in Section 5.

2. Arrangement of measurements

Four transmitters have continuously operated in the Czech Republic since January 2007. The arrangement of their locations and the location of the geomagnetic observatory Budkov is shown in Fig. 1. The geographic coordinates of the transmitters are as follows:

(1) Panska Ves: $50^\circ 32' \text{N}$, $14^\circ 34' \text{E}$, (2) Pruhonice: $49^\circ 59' \text{N}$, $14^\circ 32' \text{E}$, (3) Dlouha Louka: $50^\circ 39' \text{N}$, $13^\circ 39' \text{E}$, and (4) Kasperske Hory: $49^\circ 08' \text{N}$, $13^\circ 35' \text{E}$. Estimated locations of the reflections points are marked by crosses. We suppose that the reflections take place in the mid-points between the transmitters and receiver located at the Institute of Atmospheric Physics in Prague ($50^\circ 02' \text{N}$, $14^\circ 29' \text{E}$).

The transmitters operate at ~ 3.5945 MHz, thus, a Doppler shift of 1 Hz corresponds to a vertical velocity of 41.7 m/s. The specific frequencies of the individual transmitters differ by 4 Hz. Therefore the observed Doppler shifts can be displayed in a common Doppler shift spectrogram. In order to obtain simultaneously high frequency and time resolution of Doppler shift we apply a successive spectral analysis by shifting a Gaussian window of width ~ 10 s by a time step much less than the width of the window in the time domain. This technique enables analysis down to periods of ~ 10 s. The time assignment is controlled by a GPS clock. A short technical description of the Doppler sounding system in the Czech Republic and the primary data processing techniques has been given by Buresova et al. (2007) and Chum et al. (2008). A Digisonde Portable Sounder DPS-4 (http://ulcar.uml.edu/digisonde_dps.html) located close to transmitter #2 at Pruho-

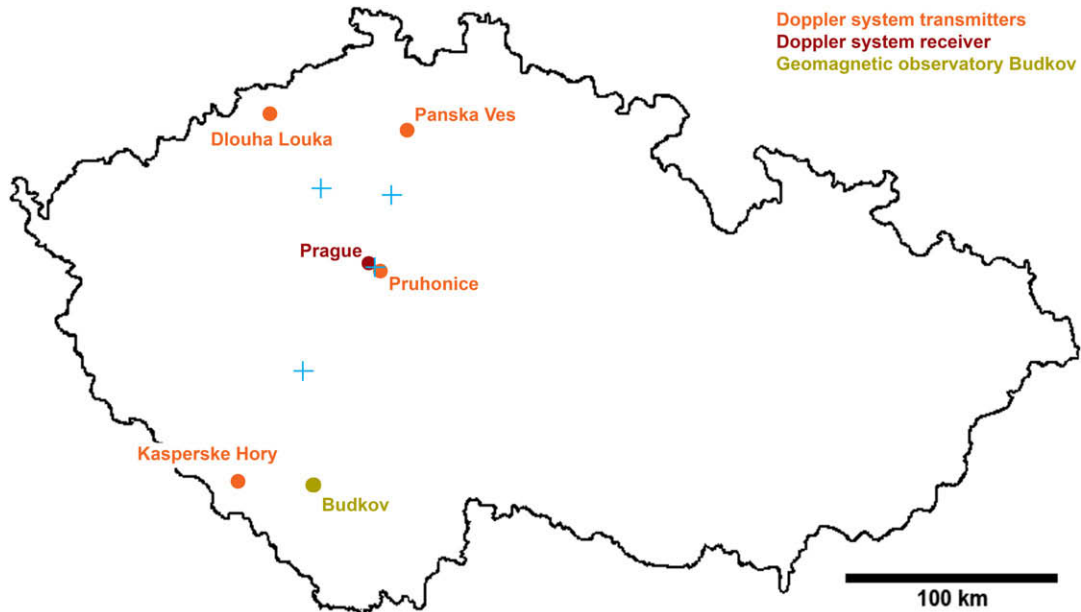


Fig. 1. Distribution of Doppler system in the Czech Republic showing locations of sounding transmitters and receiver.

nice provides ionograms used for estimating signal reflection heights.

Doppler shift measurements are compared with geomagnetic fluctuations recorded at Budkov station (49°04'N, 14°01'E) located in the south of the Czech Republic and with fluctuations measured at Niemegek (52°04'N, 12°41'E) in Germany. We use data from 3-component magnetometers sampled at 1 s intervals.

3. Observations

We observed more than 20 cases of simultaneous ionospheric oscillations and geomagnetic Pi2 pulsations in the time period from February to September 2007. Some of these pulsations are distinct and well correlated, others are relatively feeble. We selected two examples to demonstrate the characteristics of these pulsations.

The first selected example, case (1), was recorded on 7 April 2007. The Doppler shift spectrogram of ionospheric oscillations is shown in Fig. 2. Ionospheric pulsations occurred from ~1:25 to ~1:28 UT on all sounding signals. The maximum pulsation amplitude is ~0.35 Hz, which corresponds to a movement with vertical velocity of ~15 m/s. The critical frequency foF2 measured by the DPS-4 at Pruhonice during this time interval is from 2.95 to 2.97 MHz. The calculated peak heights of the F2 layer range from 299 to 301 km. Since the critical frequency was lower than the sounding frequency we conclude that we received reflections of R-X wave mode (Stix, 1992). Using ionograms we estimate that the R-X mode reflected from virtual heights of ~400 km. Corresponding geomagnetic pulsations in the north–south component (red) and the east–west component (green) recorded at Budkov are presented in Fig. 3. The fluctuations are positive if the magnetic field

vector deviates northward (eastward) from its mean orientation. In order to show only fluctuations in the frequency band of interest, we subtracted from individual signals the running means calculated over a period $T_A = 120$ s. That is, the fluctuations b_k of the B_k component at a time t_i are calculated using

$$b_k(t_i) = B_k(t_i) - \frac{1}{N_A} \sum_{j=i-N_A/2}^{j=i+N_A/2} B_k(t_j), \quad (1)$$

where N_A is the number of samples in the time period T_A and the period T_A is centered around the time t_i . All fluctuations with periods longer than T_A are strongly attenuated, which is equivalent to applying a high-pass filter with cut-off period T_A ; however, the phase shift is minimum in this case. The period $T_A = 120$ s was chosen after examining the results of the spectral analysis which is presented in the next section. Fig. 3 shows that the fluctuations in the east–west component precede the fluctuations in the north–south component. The polarization is elliptical with left-handed orientation. The maximum amplitude is almost 2 nT in both horizontal components of the magnetic field. Note also that the oscillations start at about the same time in the ionosphere and in the magnetic field, however, the magnetic pulsations last longer.

The second example was recorded on 4 May 2007 and shows two separate pulsations with the second occurring shortly after the first. Fig. 4 presents a Doppler shift spectrogram. Although the quality of signals is different for different transmitters, again the pulsations occur simultaneously on all channels. The signal from Pruhonice is partially disturbed by a ground wave. The maximum amplitude of the Doppler shift oscillation is ~0.22 Hz, which corresponds to a vertical velocity of ~9 m/s. The critical frequency foF2 measured by the

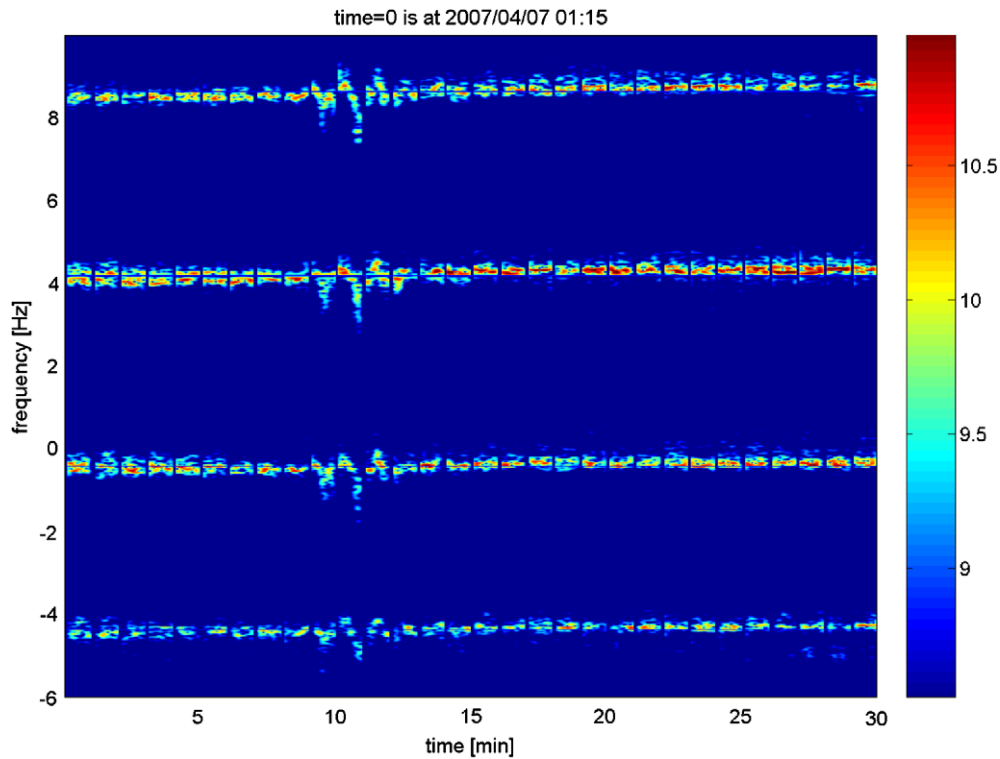


Fig. 2. Doppler shift spectrogram recorded on 7 April 2007. The record starts at 01:15 UT. Signals from top to bottom correspond to transmitters located in Kasperske Hory, Pruhonice, Panska Ves, and Dlouha Louka. Sounding frequency was ~ 3.59 MHz.

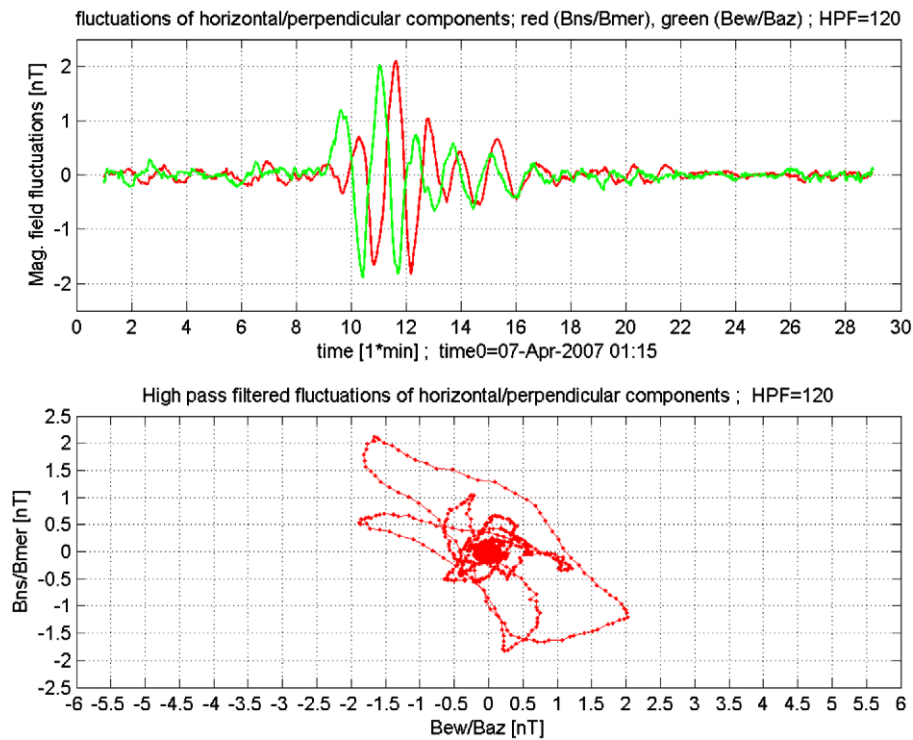


Fig. 3. Fluctuations of north–south component B_{ns} (red) and east–west component B_{ew} (green) of magnetic field measured at the Budkov Observatory. The record starts on 7 April 2007 at 01:15 UT. Periods longer than 120 s were filtered. See the text for more details. At the top: fluctuations as function of time. At the bottom: fluctuations in the horizontal plane. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

DPS-4 at Pruhonice during this time interval varies from 5.4 to 5.1 MHz. The calculated peak heights of the F2 layer range

from 275 to 265 km. Fig. 5 shows fluctuations of the horizontal components of the geomagnetic field. Only fluctuations

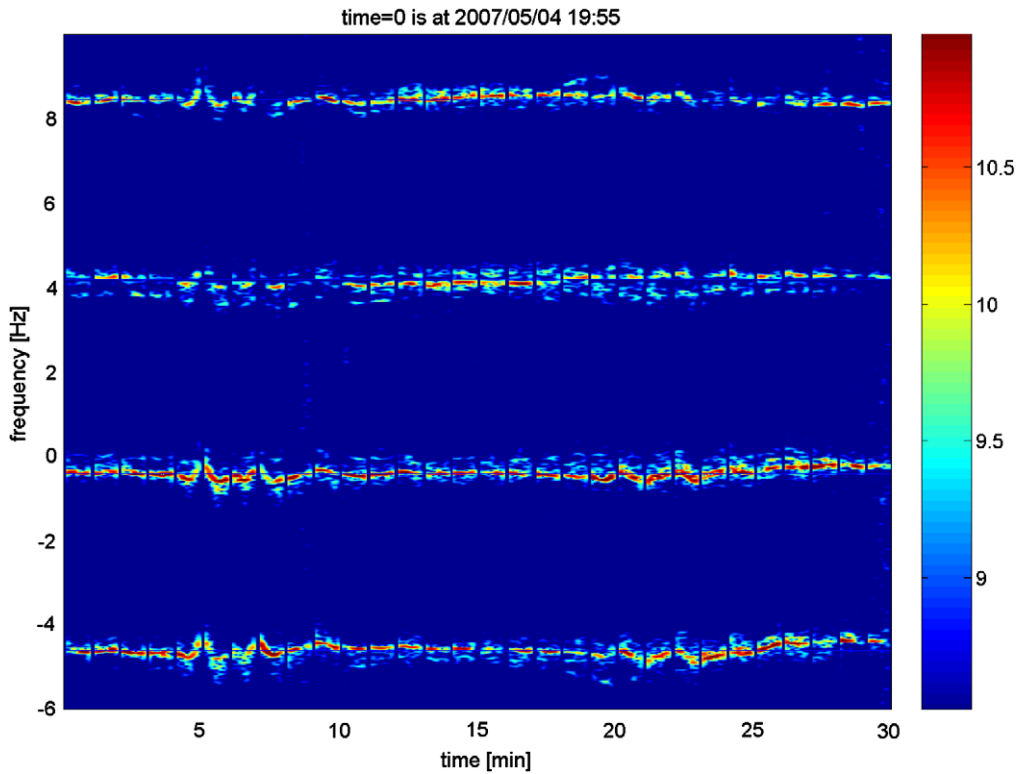


Fig. 4. Doppler shift spectrogram recorded on 4 May 2007. The record starts at 19:55 UT. Signals from top to bottom correspond to transmitters located in Kasperske Hory, Pruhonice, Panska Ves, and Dlouha Louka. Sounding frequency was ~ 3.59 MHz.

with period shorter than 240 s are displayed for this case. The filtering was done in the same way as in case 1. The color code is the same as well. The polarization of the pulsations is more

or less linear, the fluctuations in the north–south and west–east directions are in phase with the exception of the time interval from $\sim 20:02$ to $\sim 20:08$ when the components fluctuated

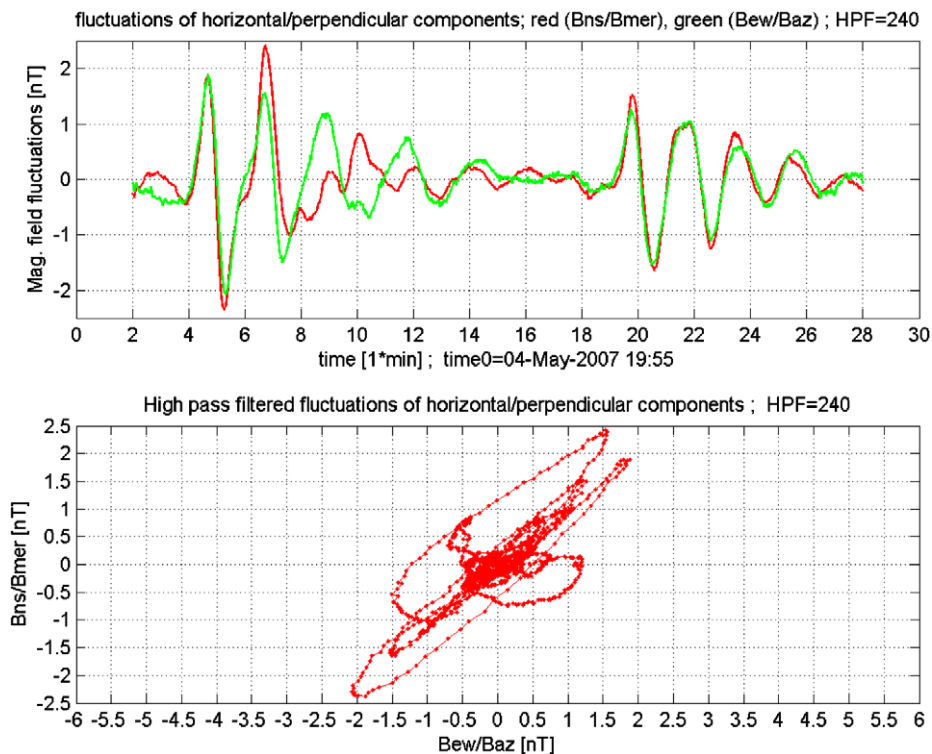


Fig. 5. The same as in Fig. 3, but for record started on 4 May 2007 at 19:55 UT. Periods longer than 240 s were filtered.

differently. In the first series of pulsations, the amplitude exceeds 2 nT, in the second series of pulsations the amplitudes are lower, ~ 1.5 nT.

The fluctuations of magnetic field magnitude are practically in phase with the fluctuations of the north–south component, but have approximately half the amplitude in most cases. Fluctuations of the vertical component of magnetic field are usually negligible (not shown). The spectral content of the pulsations and the cross-correlation between different signals is presented in the next section.

Concerning the amplitude of the Doppler shift oscillations, we should note the signal phase path, and hence also its change causing the Doppler shift depends on the vertical density profile of the ionosphere. The highest Doppler shifts are usually observed if the radio waves reflect near the F layer peak. Moreover, in the presence of horizontal gradients, a horizontal movement of the reflection layer contributes partially to the Doppler shift observed. Therefore, the vertical velocities derived from the Continuous Doppler shift measurements are approximate values. However, the fundamental frequencies (periods) detected in the waveforms observed in the Doppler shift spectrograms provide unique and reliable information.

4. Data analysis and cross-correlation of Doppler records with geomagnetic data

A mathematical analysis is relatively straightforward in the case of geomagnetic data since we have unambiguous

variations with time for each component of the geomagnetic field. In the case of the Doppler measurements, the situation is more complicated. Primarily, we record Doppler shift spectrograms – a complete Doppler shift spectrum at each time interval for which we do the calculation. The Doppler shift spectrum can exhibit one sharp peak in spectral intensity, but it can also be rather wide with spread peaks or with several peaks owing to the simultaneous reception of multiple rays (not shown). Often, one peak corresponds to the reflection of the R-X wave mode and the other to the reflection of L-O mode. If the spectrum exhibits one relatively sharp peak of spectral intensity for each sounding signal, we take a value of Doppler shift for which the spectral peak is maximum as the characteristic Doppler shift at that time. In the case of a spread spectrum, we calculate a characteristic Doppler shift as an average Doppler shift weighted by the spectral intensity (analogous to a calculation of centre of mass). Thus, we yield a characteristic Doppler shift as a single-valued function of time and can apply usual methods of signal analysis. At time intervals in which the spectral intensity is weak, we interpolate using adjacent values. The procedure of finding a characteristic Doppler shift is done automatically. In the case of ionospheric oscillations, we observe simultaneously the same Doppler shifts (within the precision of measurements) on all sounding signals. Therefore, for comparisons with geomagnetic data and for reducing possible errors in finding a correct Doppler shift, we average the characteristic Doppler shifts that we found on all signals

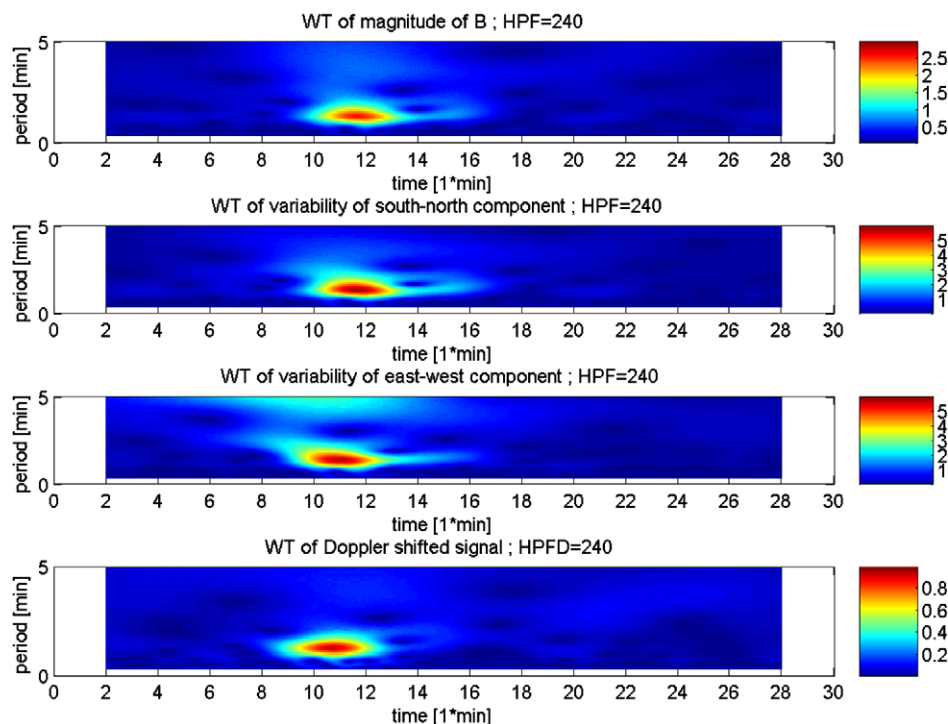


Fig. 6. Continuous Wavelet Transforms (CWT) of magnetic field and ionospheric oscillations measured by Doppler shift. The analysis starts on 7 April 2007 at 01:15 UT. From top to bottom: WT of magnetic field amplitude, north–south component, east–west component, and Doppler shift record. See text for more detail.

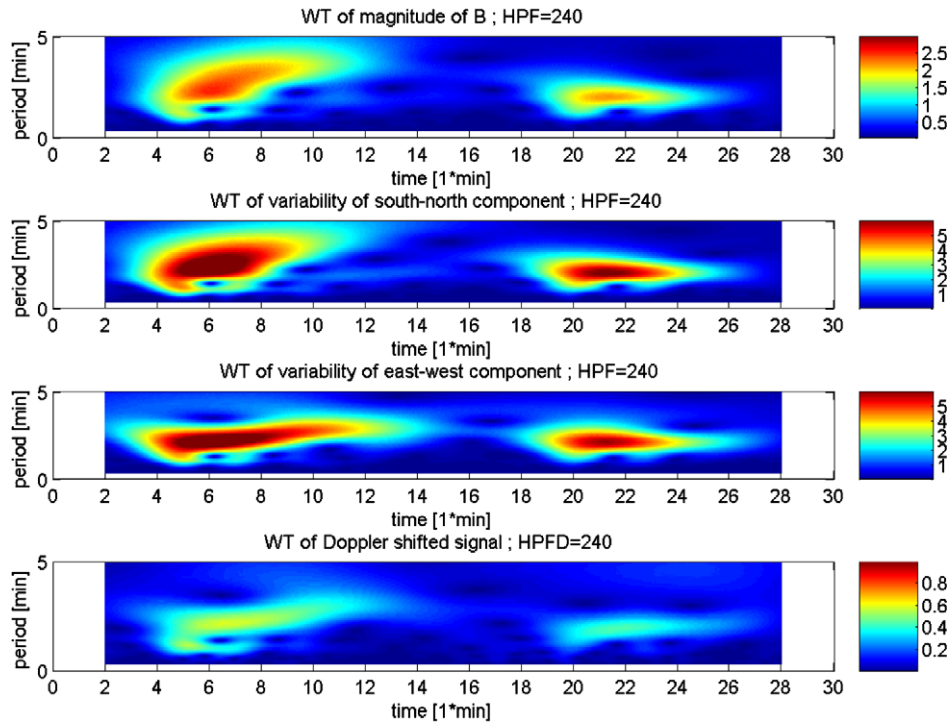


Fig. 7. Continuous Wavelet Transforms (CWT) of magnetic field and ionospheric oscillations measured by Doppler shift. The analysis starts on 4 May 2007 at 19:55 UT. From top to bottom: WT of magnetic field amplitude, north–south component, east–west component and Doppler shift record. See text for more detail.

of good quality. Thus, we have only one single-valued function of time that represents our Doppler shift measurements. We used all four signals in the first case analyzed, whereas in the second case, we used only three signals because the sounding signal from Pruhonice was not of good quality and mainly the ground wave was received. We stress that this is possible only in the case of ionospheric oscillations caused by geomagnetic pulsations. In contrast for other cases we investigate the differences and time shifts between individual sounding signals.

Having obtained Doppler shift and geomagnetic data as unambiguous functions of time, we investigate their spectral content and calculate cross-correlation functions. Since we are interested in fluctuations shorter than ~ 4 min, it is advantageous to filter out longer periods first. The filtering method was described in Section 3.

Next, we continue with a spectral analysis of the pulsations. To obtain simultaneously a maximum frequency and time resolution of spectral intensities we applied a continuous wavelet transform (CWT) based on complex Morlet wavelets. The results of CWT are displayed in Fig. 6 for case 1 and in Fig. 7 for case 2. Wavelet scalograms of fluctuations of magnetic field amplitude, north–south component, east–west component at Budkov and of a characteristic Doppler shift are shown in both figures. A high-pass filter (Eq. (1)) with $T_A = 240$ s was applied in both cases.

In the first case, example from 7 April 2007, the period of pulsations peaks around 90 s. The pulsations in Doppler shift and the east–west component precede the fluctuations

in the north–south component and the fluctuations in magnetic field amplitude. The fluctuations of periods longer than 240 s, although substantially attenuated by filtering, occurred in east–west component. They have, however, no counterpart in the Doppler shift record.

In the second case, from 4 May 2007, the spectrum is broader and exhibits larger differences between individual wavelet spectrograms, nevertheless, periods between 1 and 3 min are dominant. The fluctuations in the geomagnetic field start before the oscillation in the ionosphere. Periods longer than ~ 3 min, which also occur in the spectrum of geomagnetic fluctuations, have only weak correspondence in the Doppler shift spectrum. It seems that the Doppler shift correlates best with the east–west component.

We also present results of cross-correlation analysis between geomagnetic pulsations and ionospheric oscillations. Fig. 8 shows fluctuating signals (upper panel) and the corresponding cross-correlation functions (bottom panel) for the first case. Fluctuations with periods longer than 120 s ($T_A = 120$ s) were attenuated. The cross-correlation functions are periodic and have comparable peaks at times corresponding to multiples of the period. It is not obvious which peak of the cross-correlation function we should take to estimate correctly the phase shift between the Doppler shift signal and the magnetic data. One possibility is that the Doppler shift fluctuations are almost in phase with fluctuations of the north–south component B_{ns} and the magnitude B of magnetic field, and in anti-phase with the east–west component B_{ew} of magnetic field.

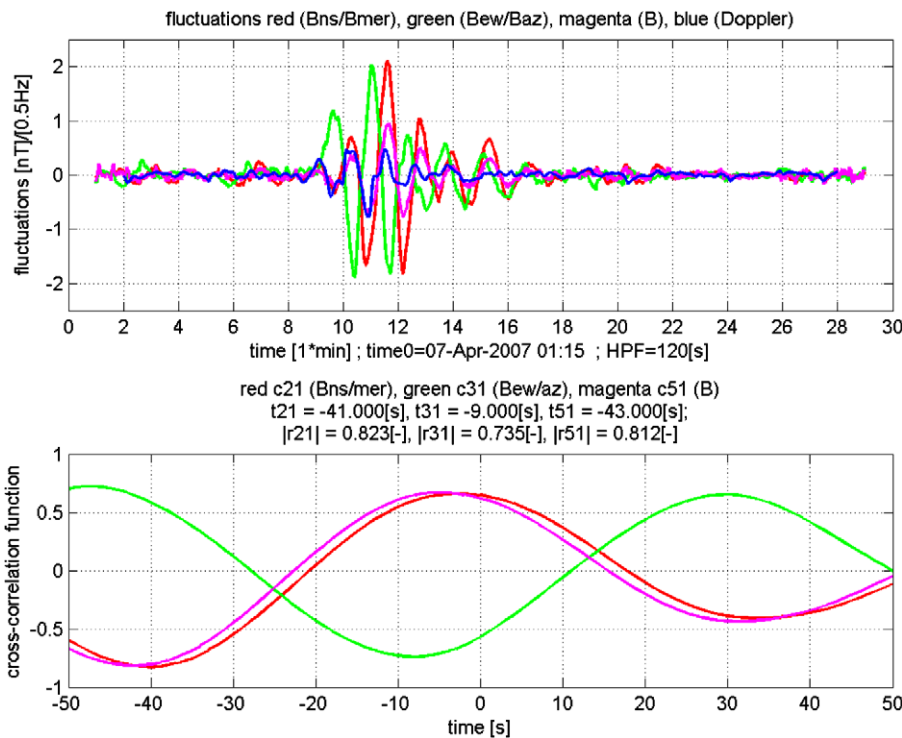


Fig. 8. At the top: fluctuations of north–south component B_{ns} (red), east–west component B_{ew} (green) of magnetic field, magnetic field amplitude (magenta) measured at the observatory of Budkov and a characteristic Doppler shift (blue). Note that the scale is 0.5 Hz in case of Doppler shift signal. The record starts on 7 April 2007 at 01:15 UT. Periods longer than 120 s were filtered. See the text for more details. At the bottom: cross-correlation functions between Doppler shift record and magnetic field. The meaning of colors follows the system from the upper panel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, taking into account the time shift obtained by the spectral analysis (Fig. 6), it is reasonable to consider that the Doppler shift signal is anti-correlated also with B_{ns} and B . Moreover, it is the anti-correlation for which we obtain the highest absolute value of the cross-correlation. The cross-correlation with the B_{ns} component is ~ -0.82 for the time shift -41 s. The cross-correlation with magnetic field amplitude is similar. The highest cross-correlation with the B_{ew} component is -0.73 for the time shift -9 s. We note that the results of the cross-correlation analysis may be misleading. The phase shifts between individual signals change, the process is not stationary. Next, the oscillations cease sooner in the ionosphere than in the geomagnetic field, which influences the cross-correlation results. Note also that all the time shifts are less than the mean period of the fluctuations which is ~ 90 s. Assuming the anti-correlation, the time shifts are comparable with one-half of the period.

The results of cross-correlation analysis for the second example, presented in Fig. 9, are less complicated. In this case, it is obvious that the ionospheric oscillations are delayed with respect to fluctuations of the geomagnetic field. Both the horizontal components and magnetic field amplitude precede the Doppler shift signal, the time shift being ~ 24 s. The maximum cross-correlation is relatively high, ~ 0.83 for the east–west component B_{ew} . The ionospheric oscillations are neither in phase nor in anti-phase

with the geomagnetic fluctuations, but are lagged by $\sim 80^\circ$. Note that the fluctuations of B_{ew} , B_{ns} , and B are in phase most of the time in this case. It is also interesting to investigate the “groups” of oscillations observed in this time interval separately. For the first group (between ~ 2 and ~ 14 min), we get the highest correlation ~ 0.87 with the B_{ew} component at the time shift ~ 23 s. For the second group (between ~ 19 and ~ 28 min), we yield the best correlation ~ 0.61 with B_{ns} component at the time shift ~ 14 s. Therefore, the groups of pulsations can be considered as separated events.

We also performed the same analysis using geomagnetic data from Niemegk (Section 2). The results are similar; nevertheless, the maxima of the cross-correlations are slightly higher for data from Budkov. This is not surprising because the Budkov station is closer to the sites of the Doppler shift observations. The B_{ew} , B_{ns} components of geomagnetic field practically oscillate in phase in Budkov and Niemegk, but the amplitudes of the oscillations are ~ 30 – 60% larger in Niemegk. The fluctuations in Niemegk also have more fine structure. This especially is true for the fluctuations of the magnetic field magnitude B where we observed larger differences, and the cross-correlation of B with the Doppler shift signal was significantly lower in case of data from Niemegk. The fluctuations of magnetic field magnitude also contained a larger portion of longer periods at Niemegk than at Budkov.

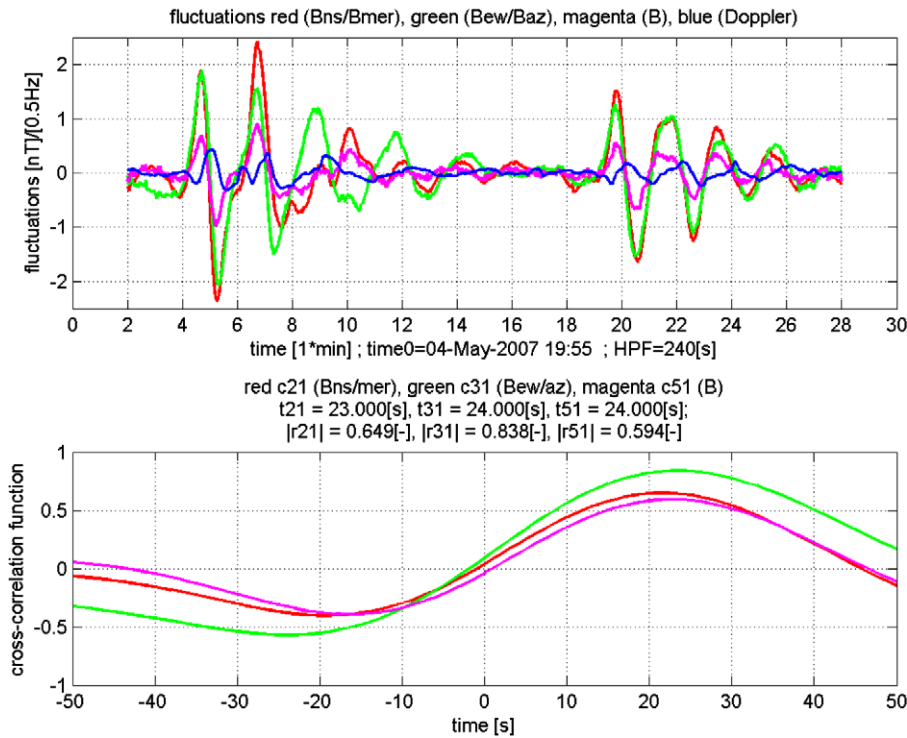


Fig. 9. The same as in Fig. 8, but for record starting on 4 May 2007 at 19:55 UT. Periods longer than 240 s were filtered.

We have found that the time/phase shifts between geomagnetic field components and Doppler shift signal vary from case to case and we have presented two examples that illustrate this. The selected examples differ in the polarization of ULF waves observed at the ground, in the frequency of the pulsations, the height of reflection of sounding radio signals and local time. An open question remains as to what influence have these factors on determining the time/phase shifts between the observations in the ionosphere and on the ground. We hope to address this question at least partially by acquiring more data in future.

5. Conclusions

Waves of periods ~1–3 min which occur simultaneously (within the precision of time resolution) on all sounding signals in Doppler shift spectrograms are well correlated with geomagnetic Pi2 pulsations. Fluctuations of the geomagnetic field with periods of ~3–5 min that occurred during the observation of Pi2 pulsations have very weak correspondence with ionospheric oscillations.

The Doppler shift signals are usually best correlated with fluctuations of the horizontal components of the magnetic field, especially with the east–west component as seen at the ground. We also observed a good correlation with fluctuations of magnetic field amplitude.

The geomagnetic pulsations analyzed were mostly left-handed with the ellipticity varying from case to case. Often, the polarization was almost linear. One case of right-handed polarization was observed.

Time/phase shifts between the components of geomagnetic field and Doppler shift signals vary from observation to observation.

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