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# A CASE STUDY OF GLOBAL ULF PULSATIONS USING DATA FROM SPACE-BORNE AND GROUND-BASED MAGNETOMETERS AND A SuperDARN RADAR

*On 21—22 January 2005 global ULF pulsations in the Pc5 range were observed in the Earth's magnetosphere. The event took place during a compact high velocity stream of the solar wind, which produced a moderate magnetospheric storm and was characterised by mainly positive values of the interplanetary magnetic field $B_z$ component and by dense plasma. To study the wave field structure of the ULF oscillations during this event we used magnetometer data from the GOES-10 and GOES-12 geostationary satellites, line of sight velocity data from the Kodiak SuperDARN radar, and magnetic measurements from INTERMAGNET observatories. In order to analyse the wave structure along a magnetic field line, GOES measurements were compared with those of ground stations closest to the GOES magnetic foot prints, while the Kodiak measurements were compared with magnetic field data from two INTERMAGNET stations, College and Shumagin, which were located within the Kodiak field of view or very close to it. The study shows a good correspondence and even coherence for some frequency components between pulsations observed near the top of a field line and at its foot and, to a lesser extent, between Kodiak line of sight velocities and conjugated magnetic measurements.*

## 1. INTRODUCTION

Ultra-low-frequency (ULF) oscillations in the mHz frequency range (Pc5 pulsations) have been the object of many investigations and a number of theories have been proposed to account for their generation. The most popular model rests on the occurrence of the Kelvin — Helmholtz instability at the magnetopause [6, 14], while other authors developed mechanisms of Pc5 generation by wave-particle interaction inside the magnetosphere [19, 28], in which case the Pc5 oscillations have usually high values of the azimuthal wavenumber $m \geq 20—30$. Moreover, a third group of possible Pc5 sources is connected with the solar wind drive of wave activity either through pulses and oscillations of the solar wind dynamic pressure [13] or through direct penetration of waves from the solar wind into the magnetosphere [12, 27], all such theories including the interaction of the excited waves with magnetospheric resonators or/and waveguides. It is well known that Pc5 are observed mainly at high latitudes, as their amplitude quickly dies out towards the magnetic equator. However, sometimes ULF oscillations fill the whole magnetosphere and are observed by space-borne magnetometers from the ionosphere up to the distant geomagnetic tail, as well as by ground stations at all meridians and all latitudes from the northern to southern polar cap. Usually this occurs when a superfast stream of the solar wind, driven by an interplanetary shock wave, engulfs the magnetosphere [16, 20]. Gogatishvili [8] was among the first to observe and analyse Pc5 pulsations at medium latitudes. P. R. Higbie et al. [10] and K. Takahashi et al. [25] described an unusually long event of global Pc5s observed, on 14—15 November 1979, by several spacecraft in the magnetosphere; for this event, J. Woch et al. [28] proposed a theory of wave excitation. C. W. S. Ziesolleck and F. H. Chamalaun [30] examined the characteristics of low-latitude Pc5s using the Australian Wide Array of Geomagnetic Stations. T. Motoba et al. [18] proposed their scenario of global

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ULF wave excitation studying a Pc5 event observed on 21 April 1993. A. Potapov et al. [20] described the main characteristics of global Pc5s which differentiate them from the common Pc5 pulsations.

ULF waves in the magnetospheric and ionospheric plasma can be detected in various ways with different sensors. The most known manifestation of these oscillations is the magnetic one, while satellites also measure the associated electric field changes and variations of plasma density and velocity. In recent years a new method to study ULF waves has appeared: radar measurements of plasma drift velocity in the ionosphere (for a review, see [7]). Each method has its own advantages and disadvantages.

In this paper we analyse an event of global Pc5 waves and highlight the correlation and coherence between waves measured by various methods in different regions of the magnetosphere. After a short description of the interplanetary conditions during the event (Section 2), we will present ULF observations in the magnetosphere and on the ground (Section 3), and the comparison between ground magnetometer data and radar line of sight ionospheric speed measurements (Section 4). Section 5 contains results of cross spectra and coherence calculations for some selected pairs of data sets. Finally, a discussion of the observations is presented in Section 6 and a summary in Section 7.

## 2. INTERPLANETARY CONDITIONS DURING THE EVENT

An interplanetary shock wave (ISW) was detected by the ACE solar wind monitor near the $L1$ libration point, at (256; –12; 19)Re GSE, on 2 January 2005, at 16:43:30 UT. Fig. 1 displays, from top to bottom and from 00:00 UT on January 21 to 24:00 UT on January 22, the following quantities: the $D_{st}$ index, the ACE 16-second GSE $B_z$ component of the interplanetary magnetic field (IMF), and the 64-second ACE ion speed and number density from 00:00 UT on January 21 to 24:00 UT on January 22. We identify the ISW thanks to the sudden increase, at 16:47 UT, of solar wind speed and plasma density from 620 to 860 km/s and from 6 to 17 cm$^{-3}$, respectively. Before the ISW, the IMF $B_z$ oscillates for about 16 hours around 0 nT with peak-to-peak excursions smaller than 10 nT; after the ISW and until 18:30 UT, $B_z$ displays oscillations with amplitudes ranging from 15 to 60 nT peak-to-peak; after 18:30 UT, $B_z$ first increases to 20 nT over 4 hours, then decreases to 0 nT over 3.5 hours; after 02:00 UT it oscillates around 0 nT. On the ground the arrival of the ISW was detected at 17:11 UT as a SSC (see ftp://www.ngdc.noaa.gov/stp/SOLAR/ftpSSC.html at NGSC), so that we can calculate an average speed between the ACE position and the Earth's orbit of approximately 950 km/s. The ACE plasma density and speed further increase at 18:20 UT, by 50 cm$^{-3}$ and 70 km/s, respectively, probably in correspondence with the ISW driving piston, lagging behind the ISW front by about 800 Earth radii. It is interesting to remark that this region behind the ISW front corresponds to the largest $B_z$ oscillations. Finally, we notice that the $D_{st}$ index clearly shows the compression due to the arrival of the ISW at the Earth, while a moderate geomagnetic storm starts a few hours later.

Fig. 2a shows spectra of the ACE $B_x$ and $B_z$ oscillations calculated over 17 hours before and 15 hours after the ISW passage, having excluded two hours of strong fluctuations after the ISW front. The spectra show two clear results: 1) the ISW yields a two- or three-fold intensification of the spectral density; 2) behind the ISW, a hump of the spectrum is ob-

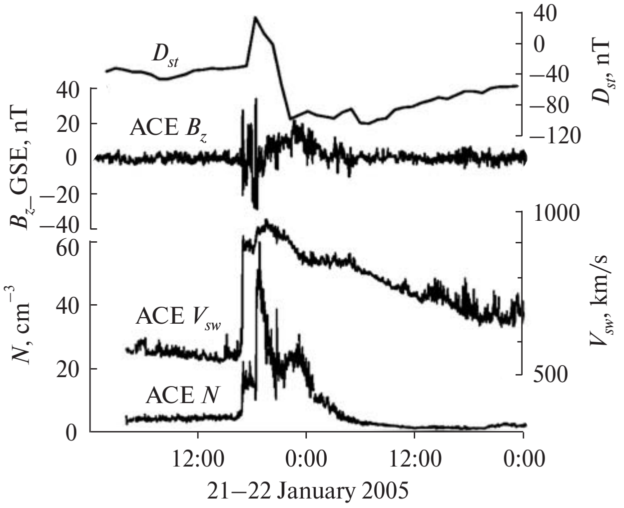

***Fig. 1.*** $D_{st}$ and IMF and solar wind parameters on 21—22 January 2005. From top to bottom: $D_{st}$ index, IMF $B_z$ component, solar wind speed and solar wind ion density. The IMF and solar wind parameters have been measured by ACE at $L1$ and have been time shifted by 28 min to account for the ballistic propagation from $L1$ to the Earth's orbit

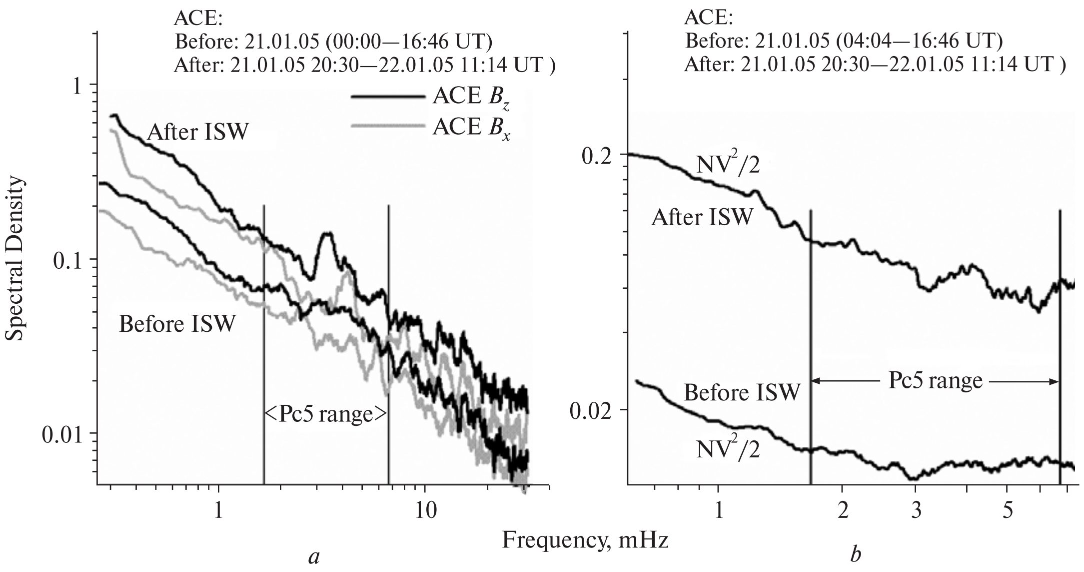

***Fig. 2.*** Spectra of magnetic fluctuations measured by the ACE magnetometer (panel *a*) and the SWEPAM experiment (panel *b*) before and after the passage of the ISW

**Geographic and corrected geomagnetic coordinates of the selected INTERMAGNET magnetic observatories, ground projections along magnetic field lines of GOES-10 and GOES-12, and approximate position of the spot in the ionosphere where the Kodiak SuperDARN radar detected Pc5 oscillations**

| Station or site | Abbreviation | Geographic coordinates | | Corrected geomagnetic coordinates | |
|---|---|---|---|---|---|
| Barrow | BRW | 71.3 | 203.4 | 70.1 | 251.4 |
| College | CMO | 64.9 | 212.2 | 65.1 | 264.2 |
| Borok | BOX | 58.0 | 38.1 | 54.0 | 113.2 |
| Sitka | SIT | 57.1 | 224.7 | 59.8 | 280.3 |
| Shumagin | SHU | 55.4 | 199.5 | 53.1 | 258.6 |
| Eskdalemuir | ESK | 55.3 | 356.8 | 52.7 | 77.4 |
| Poste-de-la-Baleine | PBQ | 55.3 | 282.2 | 65.6 | 358.6 |
| Meanook | MEA | 54.6 | 246.7 | 62.0 | 306.0 |
| Irkutsk | IRT | 52.3 | 104.5 | 47.4 | 177.4 |
| Victoria | VIC | 48.5 | 236.6 | 53.8 | 296.3 |
| Ottava | OTT | 45.4 | 284.5 | 55.9 | 1.1 |
| Honolulu | HON | 21.3 | 202.0 | 21.3 | 269.9 |
| Eyrewell | EYR | −43.3 | 172.3 | −50.0 | 256.2 |
| Kodiak field of view | Kodiak | 62 | 206 | 62 | 258 |
| GOES-10 magnetic projection | GOES-10 | 60 | 242 | 66 | 297 |
| | | −65 | 193 | −64 | 286 |
| GOES-12 magnetic projection | GOES-12 | 57 | 281 | 67 | 349 |
| | | −80 | 251 | −71 | 341 |

served, for both $B_z$ and $B_x$, between 3 and 5 mHz, i. e., roughly at the centre of the Pc5 range, while prior to the ISW the $B_x$ spectrum does not show any such feature and the $B_z$ spectrum only displays a shoulder. Fig. 2b shows the spectrum of the bulk kinetic energy pressure, $NV^2/2$, calculated from plasma parameters measured by the ACE Solar Wind Experiment (SWEPAM) before and after the ISW passage during approximately the same time intervals used for the IMF spectra. We notice that the spectrum of the solar wind kinetic energy density displays a hump between 3 and 4 mHz, i. e., similar to the one described in Fig. 2a.

## 3. PULSATIONS IN THE MAGNETOSPHERE AND ON THE GROUND

To characterise MHD oscillations in the inner magnetosphere we used data from two geostationary spacecraft, GOES-10 and GOES-12, located above the 226th and the 285th geographic meridians, respectively. Fig. 3 shows spectra of fluctuations of the magnetic $H_p$ component calculated using one minute data recorded by the two satellites. The two upper spectra pertain to a time period, between 21:00 UT on 21 January 2005 and 11:45 UT on 22 January 2005, extending over most of the interval used in Fig. 2 to calculate the "after ISW" ACE spectra. It is easy to conclude that the GOES spectra differ from those measured in the interplanetary medium. In fact, a prominent jagged structure is evident within the Pc5 range for both spacecraft. Not all spectral peaks correspond to each other, but common peaks at 1.7 and 2.6 mHz are clear. The two lower spectra are calculated from GOES-10 and GOES-12 $H_p$ measurements on 21 January 2005 between 08:00 and 17:10 UT (thus partially corresponding to the "before ISW" spectra of Fig. 2) and provide an estimate of the background wave activity before the SSC, allowing us to state that the spectral density before the SSC was about 20 times less than that after the SSC.

Table contains geographic and corrected geomagnetic coordinates of the INTERMAGNET magnetic observatories whose data will be discussed hereafter. Coordinates of the ground projections along magnetic field lines of GOES-10 and GOES-12 (determined with the Coordinate Calculator provided at the Satellite Situation Center, sscweb.gsfc.nasa.gov) are also included in Table, as well as the approximate position of the spot in the ionosphere where the Kodiak SuperDARN radar detected Pc5 oscillations of the line of sight velocity. The abbreviations listed in the second column from the left are used throughout the text. Fig. 4 displays the positions of most sites listed in Table (exception made for Borok, Eskdalemuir, and Irkutsk) plotted on a plane whose axes are the corrected geomagnetic latitude and longitude. The magnetic footprints of GOES-10 and GOES-12 are shown as black arrowed circles. The black and white triangle indicates the MLAT-MLONG cell over which we calculated the Kodiak line of sight velocities.

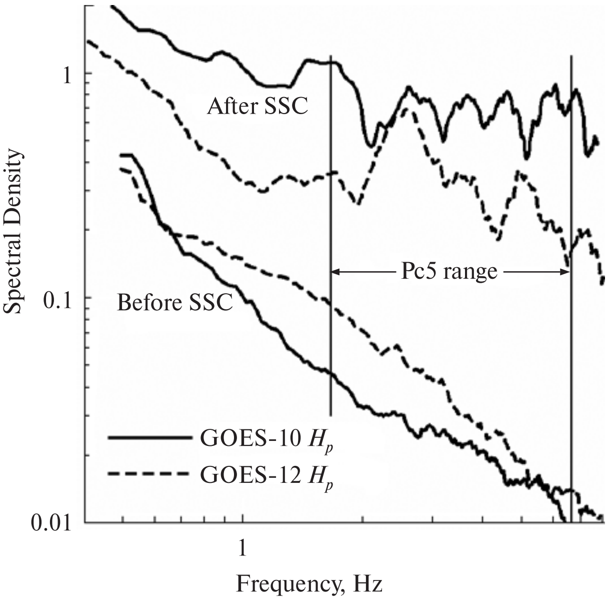

***Fig. 3.*** Two upper curves present spectra of the $H_p$ component fluctuations calculated using one minute data recorded by magnetometers of GOES-10 and GOES-12 during the interval from 21.01.2005 21:00 UT till 22.01.2005 11:45 UT. A prominent jagged structure is evident within the Pc5 range for both spacecraft. Two lower curves show spectra of the magnetic field oscillations from GOES-10 and GOES-12 measurements before SSC between 08:00 and 17:10 UT on 21.01.2005

Fig. 5 displays power spectra of ULF magnetic oscillations at eight ground stations from 19:32 UT on 21 January to 05:31 UT on 22 January. One can see that the spectra of four stations aligned approximately along one geomagnetic meridian, at middle and sub-auroral latitutes, Sitka (SIT), Shumagin (SHU), Eyrewell (EYR), and Honolulu (HON) are very similar, although they pertain to different latitudes in both hemispheres, and have two common spectral broad humps, the first roughly centred at 2.5 mHz, the second centred between 4 and 5–6 mHz. As for the remaining two stations close to the same meridian, either the higher frequency hump, at Barrow (BRW), or the lower frequency one, at College

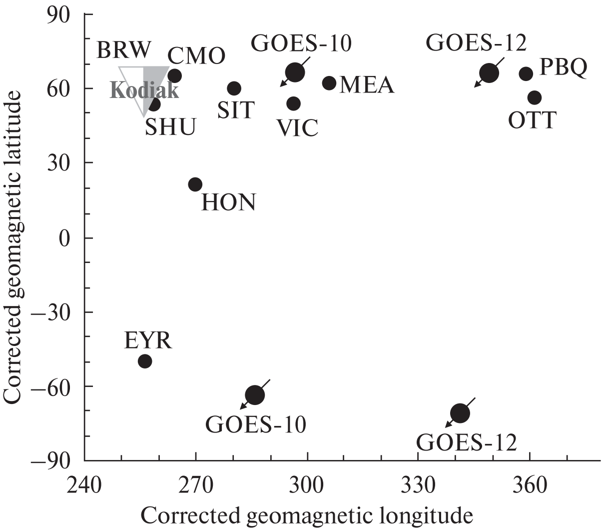

***Fig. 4.*** Schematic map showing, as black circles, the locations of the ground-based magnetic stations listed in Table (exception made for Borok, Eskdalemuir, and Irkutsk). The footprints of geomagnetic field lines threading through GOES-10 and GOES-12 are also shown as black arrowed circles. The black and white triangle highlights the position of the MLAT-MLONG cell over which the Kodiak line of sight velocities are averaged (see text for details)

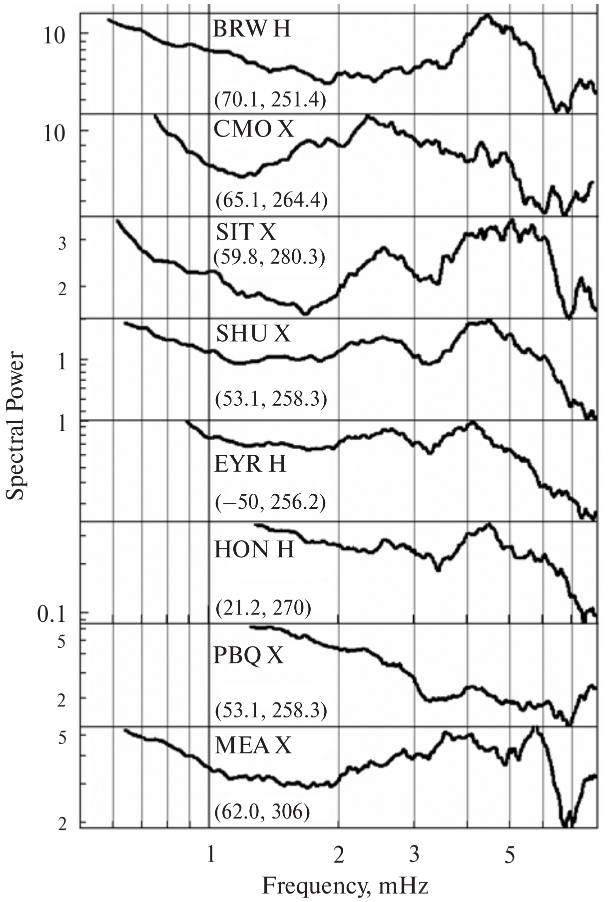

***Fig. 5***. Spectra of ULF oscillations measured at eight INTERMAGNET observatories from 19:32 UT on January 21st to 05:31 UT on January 22nd, 2005

(CMO), dominates. Moving to the last two stations included in Fig. 5, PBQ and MEA, which pertain to different meridians, we notice that, by contrast, their spectra do not display any such feature and differ considerably. In conclusion, for the time being, we may say that more differences are seen in the spectra between stations at different meridians than between stations along one meridian and that, which is rather surprising, for this particular event, at high latitudes the lower-frequency resonance seems to be localized at lower latitude than the higher-frequency resonance. We will comment more in detail on these observations in Section 6. To conclude with Fig. 5, we wish to point out that at Honolulu, at very low latitude, Pc5 oscillations have substantial amplitudes, exceeding 10 nT, while the Honolulu spectrogram (third from the bottom in Fig. 5) shows the same frequency structure in the Pc5 range as for medium and high latitudes. We interpret this as a signature of the global character of the event.

Fig. 6 shows oscillograms, between 20:30 and 22:30 UT on 21 January, of *X* or *H* components of pulsations observed at six mid-latitude observatories, all different from the stations used in Fig. 5, exception made for Eyrewell. On the right of Fig. 6 two columns list the CGM latitude and MLT of each station at the moment indicated by the arrow below the *x*-axis. All traces look rather similar, apart from the BOX and ESK traces, which were probably distorted by a high magnetic disturbance on the night side (not surprisingly, since $K_p = 7_+$). We may conclude that the Pc5 wave activity encompasses the whole planet.

## 4. COMPARISON OF GROUND MAGNETOMETER AND SuperDARN OBSERVATIONS

For our analysis we also examined the data sets of the Super Dual Auroral Radar Network, SuperDARN

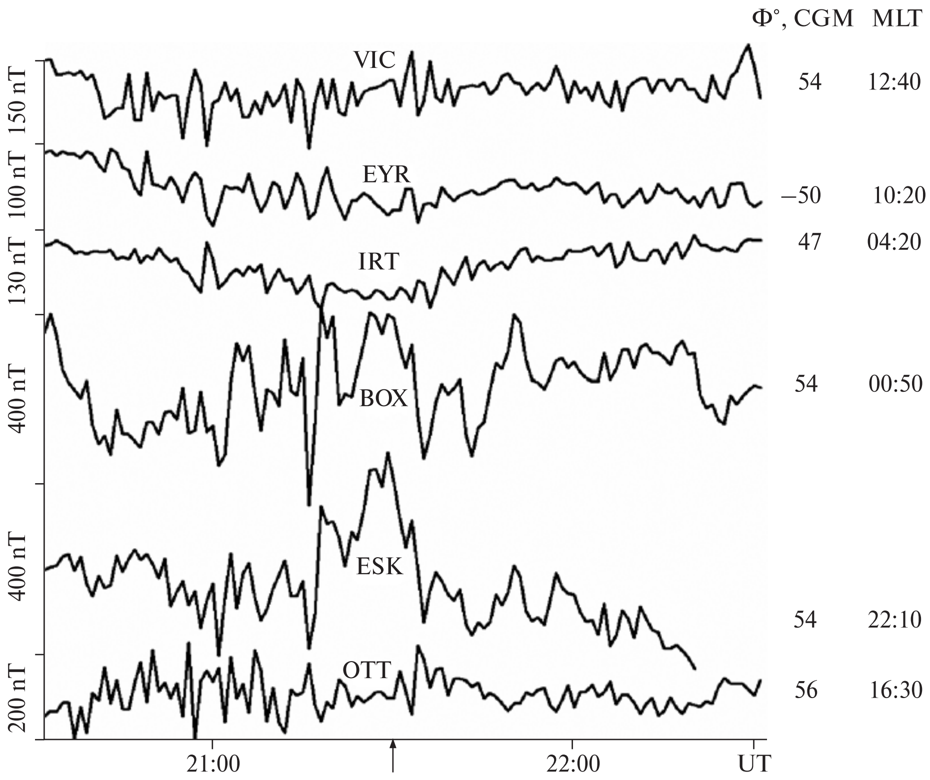

***Fig. 6.*** Oscillograms of *X* or *H* components of pulsations observed at six mid-latitude observatories between 20:30 and 22:30 UT on 21 January. For each station CGM latitude and MLT is specified on the right at the time indicated by the arrow below the time axis

[4, 9]. Each SuperDARN radar, in the common mode of operation, performs measurements of the line of sight horizontal velocity of the ionospheric plasma, between 90 and 400 km altitude, with a time resolution of 1 or 2 min, along 16 azimuthal beams separated by 3.2°, each consisting of 75 range gates between 180 and 3500 km from the radar site. For the event under study, we visually inspected all plots of SuperDARN line of sight velocity and found Pc5 signatures in some beams and ranges pertaining to the Kodiak radar. Fig. 7, in its bottom panel, shows a plot of the Kodiak 1 min line of sight velocity, averaged between 60° and 62° MLAT and over radar beams number 10 and 11 (i. e. roughly 6° in longitude, centred at 258° MLON), spanning from 00:00 UT on 21 January to 24:00 UT on 22 January; the upper panel of Fig. 7 shows a plot, over the same time interval and with the same time resolution, of the ground magnetic field *Y* component at College, band pass filtered between 1 and 6.7 mHz. As regards the meaning of the Kodiak velocity data discussed herein, it is worth recalling that the 60° and 62° MLAT interval corresponds to radar range gates 4—8, i. e. 340—560 km from the radar, which correspond to the lower limit of the ionospheric F region. Therefore, the Kodiak data shown in Fig. 7 can be interpreted as the projection along the radar line of sight of the local convection velocity of the ionospheric plasma. It appears that both the College *Y* component and the Kodiak line of sight velocity display oscillation enhancements between 17:00 UT on 21 January and 01:40 UT on 22 January (the most intensive oscillations observed by Kodiak occurred after 19:50 UT). The average amplitude of the magnetic oscillations is about 50 nT with individual peaks up to 200 nT, while the amplitude of the velocity oscillations varies between 200 and 700 m/s. Fig. 8 shows the spectrum of the Kodiak velocity fluctuations and the spectra of 1-minute resolution magnetic fluctuations from the CMO and SHU stations, which are located under the Kodiak field of view or very close to it (see Fig. 4), all calculated between 19:32 UT on 21 January and 23:59 UT on 22 January. We notice that the Kodiak spectrum displays a hump above 4 mHz, i.e. at frequencies for which the CMO and SHU spectra display a broad peak, and several peaks, among which the one cen-

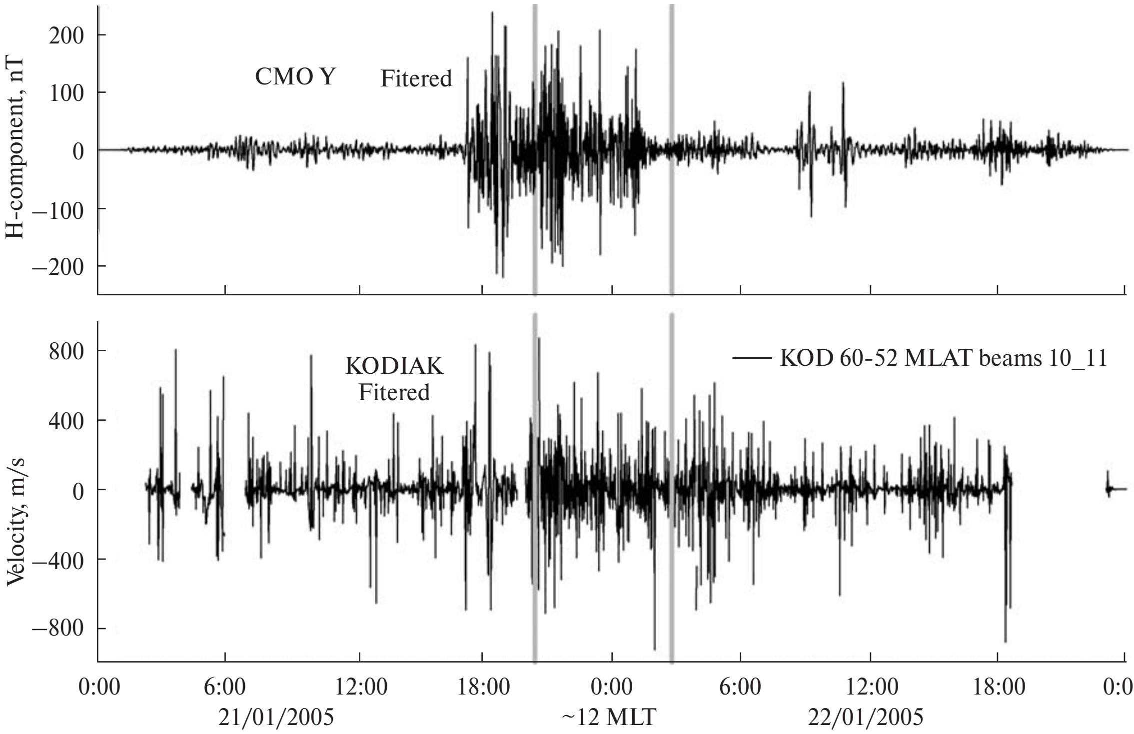

***Fig. 7.*** Time plot of the filtered CMO *Y* component (upper panel) and of the Kodiak line of sight velocity averaged between 60° and 62° MLAT for radar beams 10 and 11 (see text for details). The data between the two vertical grey lines were used to calculate the coherence spectrum

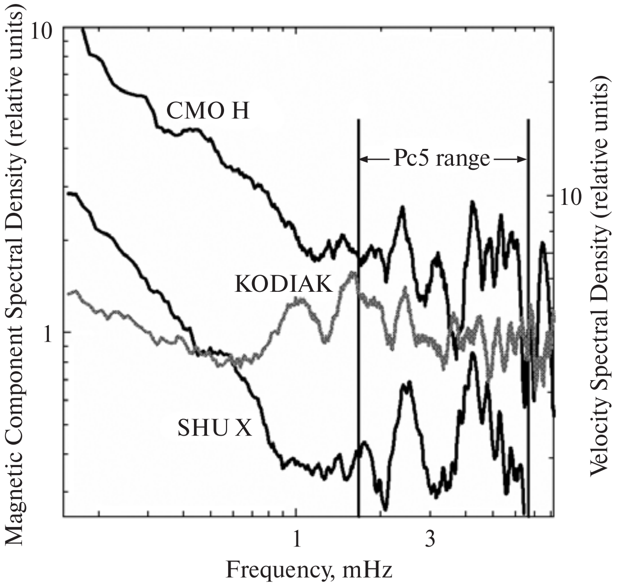

***Fig. 8.*** Spectra of ULF fluctuations of the Kodiak line of sight velocity and of the *H* and *X* components for the CMO and SHU INTERMAGNET stations, respectively. The ground stations are located under the MLAT-MLONG cell over which the Kodiak velocity was calculated (see Fig. 4)

tred at 2.5 mHz roughly coincides with a similar peak both in the CMO and in the SHU spectrum.

## 5. CROSS SPECTRA AND COHERENCE BETWEEN DIFFERENT STATIONS AND REGIONS

In order to compare spectra at various ground stations and in different regions of the magnetosphere, we applied cross-spectral and coherence analyses to the available data. For this purpose, we selected a time interval of 384 min, spanning from 20:20 UT on 21 January to 02:43 UT on 22 January, characterised by the most powerful ULF oscillations both in space and on the ground, and analysed the available data following J. S. Bendat and A. G. Piersol [3]. According to their method, in order to perform averaging in the time domain, the total interval was divided into 6 sub-intervals of 64-min each. Then each subset of data was Fourier transformed through the FFT algorithm; finally, average Fourier coefficients were obtained from the 6 sets of coefficients and

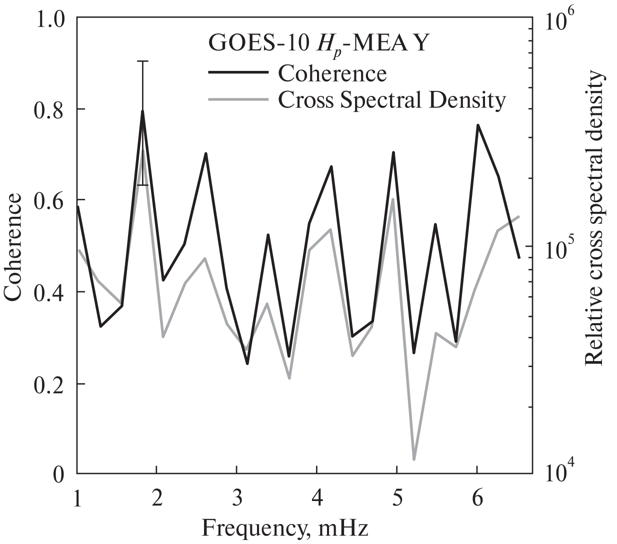

***Fig. 9.*** Coherence and cross spectral density versus frequency for the GOES-10 $H_p$ component and the MEA *Y* component. The vertical error bar shows the 95 % confidence interval corresponding to the value of the highest coherence peak (a similar bar is shown in Figs 9—12). Cross spectral density is plotted in relative units as it is not possible to safely inter-calibrate the GOES-10 and the MEA data (this same consideration applies to Figs 10 and 12)

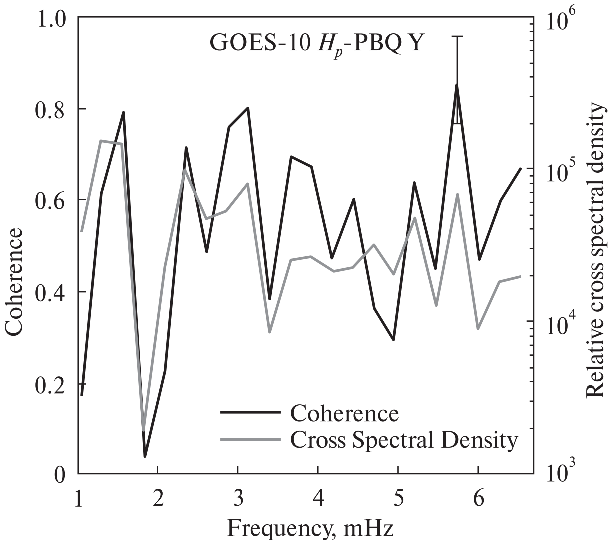

***Fig. 10.*** Coherence and cross spectral density versus frequency for the GOES-12 $H_p$ component and the PBQ *Y* component

from them we calculated matrices of spectral density, cross-spectral density and coherence for all pairs of data sets (excluding the ACE solar wind monitor) for the 1.0—6.7 mHz range, with a frequency resolution of 0.26 mHz.

First of all, let us use such matrices to examine the coherence and cross spectral density between magnetic oscillations at geostationary satellites and at the ground stations closest to the foot prints of field lines threading through them. Figures 9 and 10 show coherence and cross-spectral density plotted against frequency for the GOES-10 and MEA pair and for the GOES-12 and PBQ pair, respectively. Cross spectral density is plotted in relative units as it is not possible to safely inter-calibrate the GOES and the ground data (similar considerations apply to Figs. 10 and 12).

In Fig. 9 we see that the coherence spectrum displays several peaks, among which the two highest ones attain a value close to 0.8 at 1.8 mHz and close to 0.75 at 6.0 mHz. Here the error bar drawn at the highest peak shows the 95 % confidence interval of the calculated value of the coherence according to the definition of Bendat and Piersol [3] (error bars are drawn for the highest peak of each subsequent figure). As for the cross spectral density, we notice several peaks, generally corresponding to the coherence ones: the highest one coincides with the highest coherence peak, at 2 mHz, while no clear spectral density peak is seen in correspondence with the second highest coherence peak at 6 mHz. Fig. 10 shows that, for GOES-12 Hp and PBQ *Y*, the coherence displays several peaks, among which three have a value close to or above 0.8: at 1.5mHz, at 3.1 mHz and at 5.7 mHz. As for the cross spectral density, we also notice several peaks, generally corresponding to the coherence ones: the highest one coincides with the second coherence peak, at 1.5 mHz. Fig. 11 shows the coherence and cross-spectral density plotted against frequency for the GOES-10 and GOES-12 pair. In this case, by contrast with Figs. 9 and 10, the peaks are less pronounced and the highest coherence spectrum peak occurs at 2 mHz reaching a value below 0.7.

Finally, Fig. 12 shows the coherence and the cross-spectral density between the oscillations of the Kodiak line of sight velocities and those of the

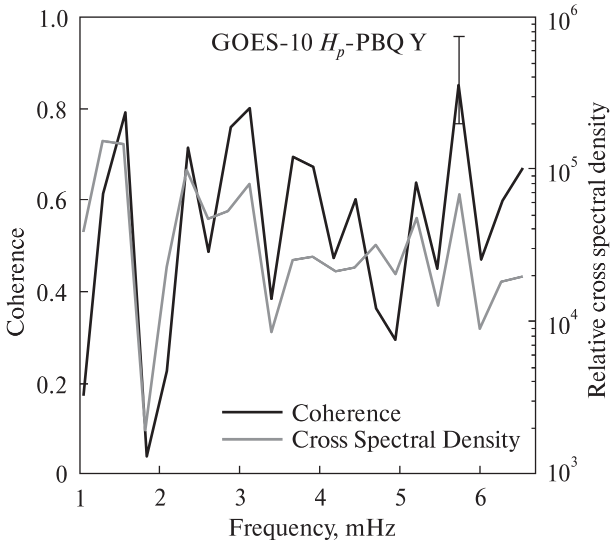

***Fig. 11.*** Coherence and cross spectral density versus frequency for the GOES-10 and GOES-12 $H_p$ component

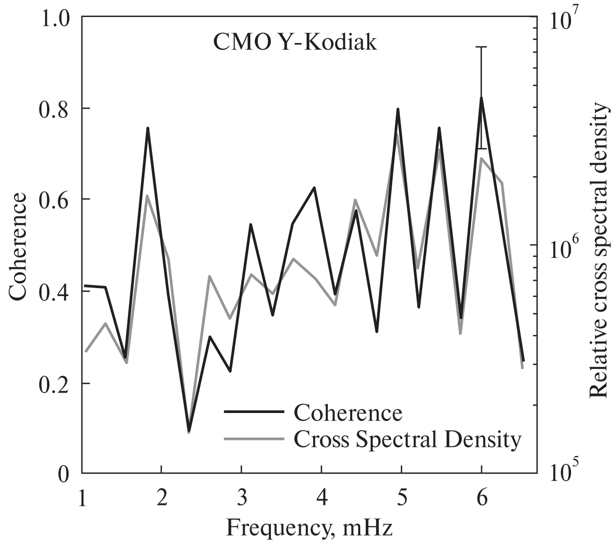

***Fig. 12.*** Coherence and cross spectral density versus frequency for the Kodiak radar line of sight velocity and the CMO $Y$ component

$Y$ component of the College ground magnetic field. Here we see that the coherence is above 0.75 at a peak centred at 1.8 mHz and at three close peaks between 5 and 6 mHz, while the relative cross spectral density also displays clear peaks at the same frequencies. Both coherent spectral regions are present in Figs. 9 and 10 as well.

## 6. DISCUSSION

We start this Section by briefly discussing the global character of the 21—22 January 2005 event. In this regard, we first of all recall that, when describing Fig. 5, we showed the homogeneous latitudinal behaviour of the spectra at the ground along one meridian, with the exception of some remarks about the spectra pertaining to CMO and to BRW (see further on in this Section), and suggested this behaviour as a signature of the global character of the phenomenon under study. Moreover, we recall that the Pc5 oscillations were observed also in the magnetosphere at different meridional planes by the GOES-10 and GOES-12 spacecraft and that we see intensive Pc5 wave activity in the whole magnetosphere during the time interval from 17:00 UT on 21 January to 02:00 UT on 22 January with spots of lower activity during successive periods up to the end of 22 January. Finally, we wish to stress the fact that Pc5 activity was also seen at very low latitudes on the ground. In conclusion, we believe that all these considerations together allow us to state that on the whole the 21—22 January 2005 Pc5 event should be classified as a global one, notwithstanding a low level of coherence between oscillations at different meridians and the shift of spectral peaks.

Before proceeding with the discussion of particular aspects of the observation described in the preceding Sections, we wish to point out that, in contrast to many previous works on Pc5 events [15, 17], our case study concerns a global event of Pc5 oscillations, which lasted for many hours on 21—22 January 2005. In this regard, we wish to emphasise that only a few Pc5 events described in the literature had a comparable or greater duration. Such an example can be found in a very unusual Pc5 event, observed on 14—15 November 1979 [10, 25], which, in contrast to the case considered in the current paper, occurred under extraordinarily quiet solar wind and geomagnetic conditions.

We recalled already in Section 1 that global Pc5 events are often connected with large scale solar wind fast streams. In this regard, A. Potapov et al. [20] showed that global Pc5 events usually occur when the solar wind speed exceeds 800 km/s. The 21—22 January 2005 event is in agreement with this previous result, as global Pc5 oscillations started immediately after the passage at the Earth's orbit of an interplanetary shock wave, when the solar wind speed jumped above 800 km/s, and died away several hours later, when the solar wind decelerated below 800 km/s. On the other hand, it has been shown that at solar minimum, when the magnetosphere is quieter, global Pc5s can be observed at lower values of the solar wind speed, down to 550 km/s [21]. The interesting feature of the 21—22 January event is that the IMF $B_z$ component was generally positive and that the ISW was only followed by a moderate geomagnetic storm. As a consequence, we had the opportunity to study the Pc5 oscillations without the simultaneous presence of large and irregular disturbances of the magnetic field (at least in the dayside and dawn sectors) which are usually associated with a major magnetic storm.

Starting from the solar wind observations, we recall that, after the ISW, the ACE magnetometer and plasma sensors showed a considerable rise of the spectral density (Fig. 2), which in the middle of the Pc5 frequency range increased by 4 times. In this regard, the most remarkable feature is that no discrete frequencies can be recognised either in the IMF spectrum or in the spectrum of density and velocity oscillations.

These features are in sharp contrast with the character of the spectra in the magnetosphere and on the ground. In fact, at the geostationary orbit (see Fig. 3) we see a set of well distinguishable spectral peaks at discrete frequencies, although the distribution of the spectral power in frequency appears to depend strongly on longitude: at GOES-10 the most powerful peak is observed at ~1.6 mHz, while at GOES-12 the spectrum maximum is shifted to ~2.3 mHz. In the 4—6.5 mHz range we even see an anti-correlation between spectral peaks at the two satellites. Almost the same picture is observed at the ground based observatories: sharp spectral peaks mainly coincide in frequency along the same meridian and are shifted to other frequencies at neighbouring meridians.

In order to reconcile the lack of high level of coherence between oscillations at different meridians and the shift of spectral peaks with the global character of the event, we make the hypothesis that high or moderate values of the oscillation azimuthal wave number $m$ are at play. This hypothesis is supported by the fact that the coherence of oscillations observed at the geostationary spacecraft and in the magnetically conjugate ground regions is high (Figures 8 and 9), but the frequencies where this high coherence is reached are different for two satellite-ground pairs. This consideration explains why a high level of coherence is never reached for the GOES-10 and GOES-12 pair and allows us to make a lower estimate of $m$ for our particular event, as the lack of correlation between the oscillations recorded by GOES-10 and GOES-12, 60° from each other at the geostationary orbit, could suggest that $m > 360/60 = 6$ (under the hypothesis of a stable dipole field). If this is so, we are lead to conclude that the covariance of ULF fluctuations measured by the two GOES satellite is poor in spite of their relatively similar spectra (see Fig. 3).

If a moderate or high value of $m$ characterises the event under study, we must briefly discuss the question as to which $m$ waves can be observed on the ground. Indeed, modes with wave numbers $k > 1/50\ \text{km}^{-1}$ cannot penetrate through the ionosphere owing to ionospheric shielding effects [11]. For the azimuthal wave number at auroral latitudes, this means strong decay for $|m| > 50$. Therefore, it is true that ground based pulsations are primarily a low $m$-number phenomenon. However, there are examples in the literature when $m$-number values of Pc5 waves are measured to be greater than $|m| \sim 15$—20 [1, 5, 24]. Moreover, G. Chisham and I. R. Mann [4] speculated that a small number of the high-$m$ Pc5 observations is connected with locality of this mode on the ground which prevents oscillations from being observed at a sufficient number of stations along existing azimuthal chains.

In conclusion, the estimate we made earlier that $m > 6$ and the consideration that past works cite values of the order of 15—20 as realistic for propagation down to the ground, leads us to suggest that we are actually dealing with a global PC5 event characterised by moderate $m$ numbers.

We now move to the issue of the observed field structure along a meridian. In this regard, we have noticed that the higher frequency peak exceeds the lower frequency ones at auroral latitudes as compared with mid-latitudes (Fig. 5). Indeed, the maximum spectral power in the 2—3 mHz range is observed at College (65.1° MLAT), whereas in the 4—5 mHz band we have a prominent maximum at Barrow (70° MLAT) or at higher latitude. Similar observations were reported by C. W. S. Ziesolleck et al. [31] from radar data. They observed both the 1.3 mHz and the 1.6 mHz signals to peak at almost the same latitude near 70° MLAT. C. W. S. Ziesolleck et al. [31] explained this effect by amplitude and/or frequency modulation. In our case, the observations probably stem from the wave energy distribution between harmonics of the field-line oscillations along the magnetic field, as it appears that we see a mix of several harmonics, whose relative contributions can change with time and, probably, subject to the external forces. In this regard, if we suppose that the observed maxima of the spectral power along a meridian correspond to the field line resonance locations, we can assume that, in this case, more than one harmonic are involved in the FLR pattern. For example, 2.5 mHz could correspond to the first harmonic of the College field line exceeding the fundamental frequency of the Barrow field line. Under this scheme, the third harmonic of the Barrow field line could lie between 4 and 5 mHz and provide a spectral power maximum at Barrow. As an alternate interpretation, we may infer that, under disturbed magnetic conditions, Barrow could find itself in the polar cap, so that the oscillations observed there could have quite a different nature, such as to be due, for instance, to penetration from the geomagnetic tail.

The difference which we have observed between the solar wind and the magnetospheric spectra, leads us to discuss the issue of the relation between them, as in recent years a number of works appeared which suggest the extra-magnetospheric origin of ULF waves in the Pc5 range [12, 13, 27]. A. D. Walker [27] proposed that the spectrum arises in the solar wind and argued that the stability of the set of frequencies observed by a number of authors [17, 22, 23] stems from the stability of the spectrum of waves coming from the solar wind. However, no mechanism was suggested for the Pc5 generation in the solar wind. R. L. Kessel et al. [13] also described discrete frequencies in the solar wind and in the magnetosheath, but remarked that only some of them coincide with the values observed at the Earth's surface. Our results show that oscillations in the Pc5 range are present in the solar wind during a period when global Pc5 oscillations are observed in the magnetosphere; however, as far as our event is concerned, the spectrum in the solar wind is clearly continuous, while in the magnetosphere we observed discrete spectral peaks at different latitudes along the same meridian; moreover, the peaks appear at different frequencies depending on magnetic longitude. If we wish to assign a "driving" function to the solar wind Pc5 oscillations for the 21—22 January 2005 event, it would be necessary to envisage a magnetospheric mechanism by which the energy of the solar wind waves would be redistributed over discrete frequencies. Maybe, a first step toward the development of such a mechanism has been made by A. N. Wright and G. J. Rickard [29] in their numerical study of the response of a 1D magnetohydrodynamic cavity to the impact of a random motion which has a broadband frequency spectrum. We admit that our case study cannot provide an answer to this problem, but it certainly advocates for additional investigations to be pursued.

After treating the issue of the possible solar wind origin of Pc5's, we must further comment on the spectral peaks which we see in the magnetosphere. Many authors [17, 22, 23, 27] presented evidence of the existence of a set of discrete and remarkably stable ULF "favoured" frequencies in the magnetosphere at 1.3, 1.9, 2.6 and 3.3 mHz. On the other hand, C. W. S. Ziesolleck and D. R. McDiarmid [32] suggested that different techniques of data processing can give different results as regards the position and stability of such spectral peaks. This could be the case of our results as well. In fact, in Figure 3 we observed common peaks for GOES-10 and GOES-12 at 1.7, 2.6, 3.7, and 6.9 mHz, among which only the 2.6 mHz peak coincides with one of the so-called "favoured" frequencies. On the other hand, a reason for this discrepancy could also be that all the above cited papers [17, 22, 23, 27] dealt with auroral Pc5 pulsations observed mainly in the midnight or early morning hours, while our study refers to global Pc5 oscillations encompassing the whole magnetosphere. In this regard, it is also worth recalling that U. Villante et al. [26] discussed four events for which "favoured" frequency peaks were observed in the Pc5 range at medium latitudes, although, in each of the analysed events, only some "favoured" frequencies were observed at the same time.

As regards the correlation between the Kodiak line of sight velocity and magnetic oscillations at the CMO station, we found a value close to 0.8 (Fig. 11). This can be considered as an acceptable value, in view of the fact that this cross analysis involves two different physical quantities. Moreover, the SuperDARN line of sight velocity data were averaged over a 200 × 600 km cell, while the magnetometer data usually refer to a 1000 × 1000 km region in the ionosphere above the magnetometer itself.

## 7. SUMMARY

Hereafter we present a short summary of our finding based on a case study of global Pc5 oscillations in the magnetosphere.

1. Although there was enhanced background of ULF activity in the Pc5 band upstream of the Earth, we could not find any resonant structure in the oscillations outside the magnetosphere in contrast with A. D. Walker's [27] hypothesis about the extra-magnetospheric nature of the Pc5 resonant structure on the ground.

2. We found a better correspondence between ULF activity observed along one meridian at various latitudes than between ULF waves measured along one parallel at different meridians. The same relates to oscillations in space: coherence between Pc5 pulsations observed near the top of a field line and at its foot is much higher than that between two geostationary satellites located at different meridians. This is partially new, as similar considerations were made in the past by V. B. Belakhovsky and V. A. Pilipenko [2].

3. The correspondence between variations of Kodiak line of sight velocity and magnetic oscillations turned to be relatively high, at least not lower than that between magnetic pulsations at neighbouring meridians. This confirms previous results of C. W. S. Ziesolleck et al. [31].

4. Neither on the ground, nor in the space, we found a stable series of discrete frequencies in the Pc5 observations, as it was reported in several earlier papers [17, 22, 23, 27].

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## ГЛОБАЛЬНЫЕ УНЧ-КОЛЕБАНИЯ, НАБЛЮДАВШИЕСЯ СПУТНИКОВЫМИ И НАЗЕМНЫМИ МАГНИТОМЕТРАМИ И РАДАРОМ SuperDARN: АНАЛИЗ КОНКРЕТНОГО СОБЫТИЯ

21—22 января 2005 г. в магнитосфере Земли наблюдались глобальные УНЧ-колебания в диапазоне Pc5. Событие произошло на фоне умеренной магнитосферной бури, вызванной компактным высокоскоростным потоком солнечного ветра, при положительном значении составляющей $B_z$ межпланетного магнитного поля и при высокой плотности плазмы. Для изучения структуры волнового поля УНЧ-колебаний во время этого события мы использовали данные магнитометров геостационарных спутников GOES-10 и GOES-12, данные о скорости ионосферной плазмы вдоль луча зрения радара Kodiak системы SuperDARN и магнитные измерения на обсерваториях сети INTERMAGNET. Чтобы проанализировать волновую структуру вдоль силовой линии геомагнитного поля, измерения на GOES были сопоставлены с измерениями наземных станций, наиболее близким к магнитной проекции спутников GOES, а измерения радаром Kodiak сравнивались с двумя станциями сети INTERMAGNET, Колледж и Шумагин, которые были расположены в пределах поля зрения радара или близко к нему. Результаты показывают хорошее соответствие и даже когерентность для некоторых спектральных составляющих между пульсациями, наблюдавшимися вблизи вершины силовой линии и в ее основании, и в меньшей степени — между вариациями скорости плазмы вдоль луча зрения радара и сопряженных магнитных измерений.

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### ГЛОБАЛЬНІ УНЧ-КОЛИВАННЯ, ЯКІ СПОСТЕРІГАЮТЬСЯ СУПУТНИКОВИМИ ТА НАЗЕМНИМИ МАГНІТОМЕТРАМИ І РАДАРОМ SuperDARN: АНАЛІЗ КОНКРЕТНОЇ ПОДІЇ

21—22 січня 2005 р. у магнітосфері Землі спостерігалися глобальні УНЧ-коливання в діапазоні Pc5. Подія сталася на тлі помірної магнітосферної бурі, викликаної компактним високошвидкісним потоком сонячного вітру, при позитивному значенні складової $B_z$ міжпланетного магнітного поля і при високій щільності плазми. Для вивчення структури хвильового поля УНЧ-коливань під час цієї події ми використовували дані магнітометрів геостаціонарних супутників GOES-10 і GOES-12, дані про швидкість іоносферної плазми вздовж променя зору радара Kodiak системи SuperDARN і магнітні вимірювання на обсерваторіях мережі INTERMAGNET. Щоб проаналізувати хвильову структуру вздовж силової лінії геомагнітного поля, вимірювання на GOES були зіставлені з вимірами наземних станцій, найбільш близькими до магнітної проекції супутників GOES, а вимірювання радаром Kodiak порівнювалися з двома станціями мережі INTERMAGNET, Колледж і Шумагін, які були розташовані у полі зору радара або близько до нього. Результати показують хорошу відповідність і навіть когерентність для деяких спектральних складових між пульсаціями, що спостерігалися у районі вершини силової лінії і в її основі, і меншою мірою — між варіаціями швидкості плазми вздовж променя зору радара і пов'язаних магнітних вимірів.