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Global observation of 24 November 2006 Pc5 pulsations by single mid-latitude underground [SQUID]^2 system

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Abstract. On 24 November 2006, simultaneous observations of Pc5 pulsations, electron precipitation and whistler-mode chorus, as well as solar wind and IMF parameters have been analyzed based on data from IMAGE magnetometers, riometer array and temporal VLF station. This paper focuses on the Pc5 pulsations detected at the same time, in the 1–25 millihertz range, by the [SQUID]^2 system (SQUID magnetometer within a **S**hielding **QU**alified for **I**onosphere **D**etection) installed 518 m underground at 43.92° N, 5.48° E. As expected, the 3-D-frequency spectrum of these mid-latitude [SQUID]^2 signals exhibits frequency peaks quasi identical to those observed by polar stations of close geomagnetic longitude. The signal/noise ratio allows the observation of the wave polarization and the beatings of the frequencies. As a result, the possibility of studying, at mid-latitude, magnetic Pc5 pulsations linked with an event in the magnetosphere can improve the description of both behaviour and propagation of these waves.

Keywords. Ionosphere (Ionosphere-atmosphere interactions)

1 Introduction

Never in equilibrium, the magnetosphere undergoes changes of plasma and field properties which excite normal modes as field line resonances (FLRs), cavity modes and wave guide modes (Kivelson and Southwood, 1985; Allan et al., 1986; Samson et al., 1992). As well as internal disturbances like magnetic storms (Kozyreva and Kleimenova, 2009; Pilipenko et al., 2010), fluctuations in the solar wind dynamic pressure also drive waves in the magnetosphere (Stephenson and Walker, 2002; Kepko and Spence, 2003). Their properties and generation mechanisms are still being elucidated. Generally, these waves are easily identified at polar latitudes (Yagova et al., 2002; Sung et al., 2006) as these sites provide a viewing window through which nearly all the regions of geospace (outer space near the Earth, including the upper region of the atmosphere, as well as the ionosphere and magnetosphere) are remotely sensed by direct connection between the ionosphere and the magnetosheath. Depending on their origin, Ultra Low Frequency (ULF) pulsations can be classified over frequency intervals corresponding to the Pc1 to Pc5 bands (from 5 Hz to 1 mHz).

The event of 24 November 2006 is reported in the literature and analyzed through simultaneous multi-points Scandinavian stations by comparison with solar wind conditions (Manninen et al., 2010). These results show a relationship between Pc5 ULF pulsations, electron precipitation, whistler-mode chorus, solar wind and IMF parameters. Our interest is that the pulsations, recorded from several IMAGE magnetometers at polar latitudes can be a reference to compare the magnetic signals recorded at mid latitudes and different longitudes, on the same date, using underground high sensitivity magnetometry in an ultra low-noise environment. Underground measurements of geomagnetic fluctuations in the mHz band are rare (Villante et al., 1998) and detection of geospace phenomena at geographic latitude below 60° is seldom observed because of the sharp wave attenuation with latitude. In addition, the anthropogenic magnetic noise being larger may overcome these weak natural signals. In this context, the [SQUID]^2 system, described in the next section,

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presents a substantial asset for detecting weak natural signals because it offers a low-noise recording environment at mid-latitude. [SQUID]^2 has been successfully used for establishing the first three-component experimental spectrum of the magnetic-background noise, under quiet seismic and magnetic environmental conditions, showing that among the several resonances recorded, some of them could be reasonably attributed to the Earth's eigenmodes (Marfaing et al., 2009). At millihertz frequencies, these extremely long wavelengths ensure that any instrument is always in the near-field regime for any magnetic source on Earth and thus offers reliable information for detecting any event occurring in a spatial environment of dimension comparable or larger than the Earth.

The choice of a well studied event (Manninen et al., 2010) analyzed from Scandinavian observations obtained along geomagnetic meridians between 107° and 110°, provides a reference for our investigation with [SQUID]^2 performed at Corrected Geomagnetic Coordinates (CGC) 38.09° N latitude and 80.94° E longitude. Section 2 is devoted to the instrument description and the data analysis techniques in the millihertz range. Section 3 discusses the spectra detected by [SQUID]^2 by comparison with conventional magnetic observatories at high latitudes and centred on two different longitudes, one of them being the [SQUID]^2 one. Section 4 discusses with some Pc5 wave characteristics concerning their propagation and polarization and Sect. 5 presents our conclusions and prospects.

2 Instrument and data analysis

2.1 The ultra-low–noise [SQUID]^2 magnetometer

Our measuring device is an unique combination of a sensitive 3 axis low T_c SQUID magnetometer (StarCryo ©) within the launching control room no. 1 of the former French nuclear missiles acting as a Shielding Qualified for Ionosphere Detection (hence [SQUID]^2) (Waysand et al., 2000, 2009). Located in the Laboratoire Souterrain à Bas Bruit de Rustrel, France (LSBB, http://lsbb.oca.eu) [SQUID]^2 is currently used to explore the daily geomagnetic field variations, giving information on the magnetic response. This magnetometer is a passive ground sensor which, at these extremely low frequencies, is always in the near-field for any signal source on Earth. This gives global information of world-wide magnetic effects that are sensitive, for example, to seismic waves (Gaffet et al., 2003). It is thus tempting to recognize the limits of such an instrument by investigating magnetic excitations of the atmosphere/ionosphere.

The performance of the shielding was measured from 1 to 1000 Hz, using a 3-axis SQUID (Waysand et al., 2000). Inside this 1250 m^3 shielded capsule, the electromagnetic noise level is lower than 3 fT/$\sqrt{}$Hz above 40 Hz. The capsule is not a zero Gauss chamber. With an overburden of 518 m of limestone rock and 2 m of reinforced concrete and 2 cm of steel, this chamber, which is not-magnetically shielded, behaves as a low-pass filter. It allows SQUID detection of magnetic signals less than 40 Hz without being polluted or saturated by high frequency noise. The variations of the permanent geomagnetic field are recorded along the three axes of a geographic system (NS for the North-South component, EW for the East-West component, and Z for the vertical component). The instrument is permanently set at a place where the fluctuations of the magnetic field are minimum all around the instrument to avoid SQUID saturation; this was made by a crude mapping inside the capsule. The very low environmental mechanical noise is monitored using a 3-D broadband seismic array. The absence of anthropogenic activities within two kilometers ensures that the recorded signals are not parasitic signals produced by the long-distance effects of railways (Lowes, 2009) or by high-voltage power lines, as the LSBB laboratory is situated in the National Park of Luberon in France (geographic coordinates 43.92° N, 5.48° E). The seismic noise spectrum of LSBB area is near to the theoretical worldwide minimum, so no movement of magnetic masses generated by mechanical parasitic movements can perturb magnetic observations.

A comparative calibration between [SQUID]^2 and others SQUID vertical magnetometers has been conducted at the LSBB site in March and September 2006 (Henry et al., 2008). Over 12 h a good agreement was obtained with the linear interpolation of the vertical component measured at 3 magnetic observatories around LSBB (Chambon la Forêt in France, Ebro in Spain and Fürstenfeldbruck in Germany).

A significant test of system performance has been the detection of a hydro-seismo-magnetic response to the ground P-wave excitation generated by the MW 7.6 Bhuj, India earthquake centered 6250 km away: magnetic related perturbations were in the tens of pT (Gaffet et al., 2003).

2.2 Data processing techniques

Initially, the system was developed for the study of earthquake magnetic signatures. Thus, it uses acquisition stations and procedures compatible with the 3-D LSBB seismometer array, with a sampling rate of 125 Hz. The three-component responses of the seismometer near the capsule (named RAS), filtered between 0.01 and 10 Hz are confronted daily jointly with the two SQUID 3 components magnetograms (MGN), one filtered in the same frequency range, the other unfiltered. This continuous survey provides a first qualitative daily characterization allowing, at a glance, a crude classification:

1. completely quiet days,
2. magnetically quiet days with major earthquake activity,
3. magnetically agitated days (possibly including magnetic storms or rare phenomena such as solar eclipses) but seismically quiescent,

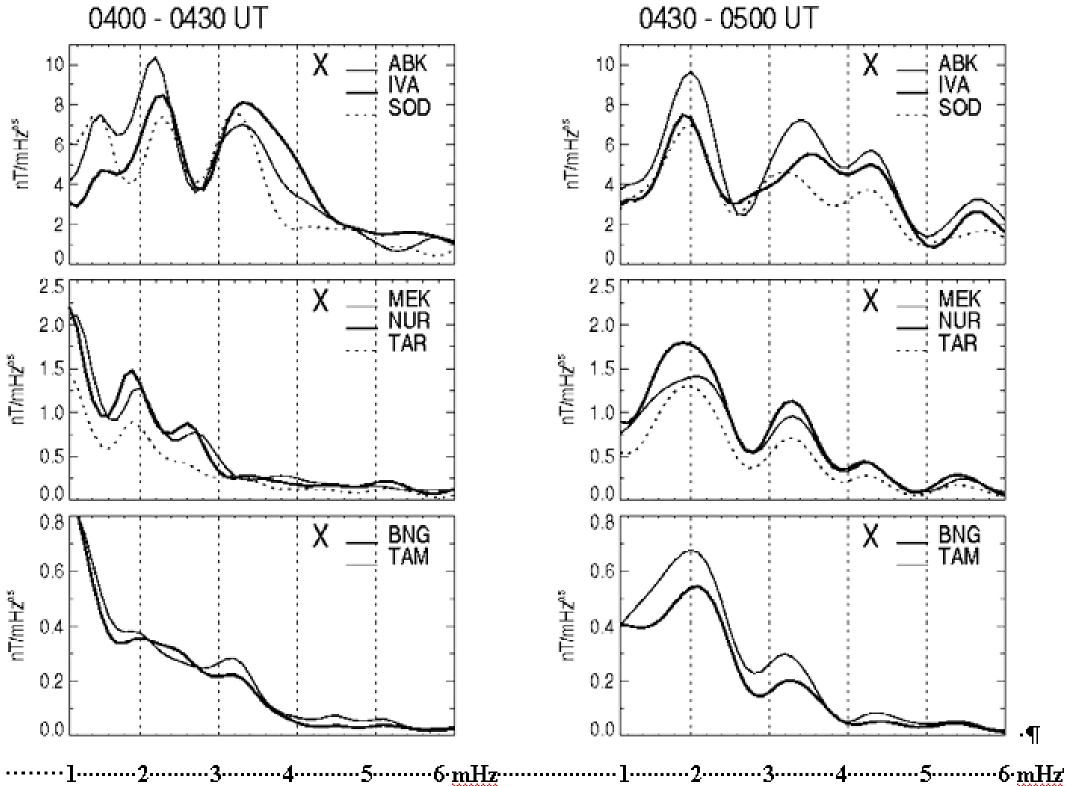

Fig. 1. Spectra of the geomagnetic pulsations at polar and lower latitude stations along geomagnetic meridians of about 107°–110°, concerning sequence 1 (left: 04:00–04:30 UT) and sequence 2 (right: 04:30–05:00 UT) (part of Fig. 4 in Manninen et al., 2010).

4. days which are neither magnetically nor seismically quiet.

This crude classification can be confirmed or completed by information and alerts received from dedicated networks (e.g. NEIC for a world-wide list of earthquakes, RENASS for earthquakes in the vicinity of Rustrel, INTERMAGNET for a daily survey of the global geomagnetic field and NOAA space weather).

Fast Fourier Transform (FFT) spectral analyses are carried out, after resampling at 1 Hz, using conventional tools (apodisation and detrend of the magnetograms). The time interval of 30 min between the 2 sequences is long enough to validate the observed frequency variation in the millihertz band and, using the zero padding method, the spectral resolution is 0.055 mHz in the range of 1–500 mHz.

3 The 24 November 2006 ULF spectrum

On 24 November 2006, Manninen et al. (2010) have identified geomagnetic pulsations in the Pc5 frequency band (1.7–6.7 mHz) in the magnetic data from several IMAGE stations located along the geomagnetic meridian of about 107°–110°, at high (63.8° to 67.2°) or lower (54.4° to 59.1° and 5° to 8.5°) latitudes. Frequencies detected in the time interval 04:00–04:30 UT are different from those in the 04:30–05:00 UT time interval. Amplitude spectra of the ULF pulsations recorded at these different stations are displayed in Fig. 1 for the two time sequences (left and right panels – data from Manninen et al., 2010). The code of each station is indicated on the figure.

For all polar stations, the first time interval (04:00–04:30 UT) spectra show three peaks at about 1.4 mHz, 2.3 mHz, and 3.2 mHz. In the second time interval (04:30–05:00 UT) four peaks are observed around 2.0 mHz, 3.5 mHz, 4.2 mHz, and 5.5 mHz. In the two sequences, their amplitudes decrease with the latitude.

To start a pertinent comparison, the amplitude spectral density (ASD) is extracted from the 3-D magnetograms recorded at MGN-LSBB-Rustrel, considering the two same frequency ranges and time sequences, as seen in Fig. 2 (top panels). The comparison of our results is made for the NS component, equivalent to the X direction shown in Manninen et al. (2010). During the first sequence (04:00–04:30 UT), in the 1–6 mHz range, the domain of the Pc5-type pulsations, discrete emissions are pointed on the components NS, EW and Z. For NS and Z, the frequencies are at 1.22 mHz, 1.91 mHz, 2.51 mHz, 3.11 mHz, 3.75 mHz, 4.31 mHz, 4.88 mHz, 5.39 mHz, and 5.96 mHz, while some shift exists for EW. During the second sequence

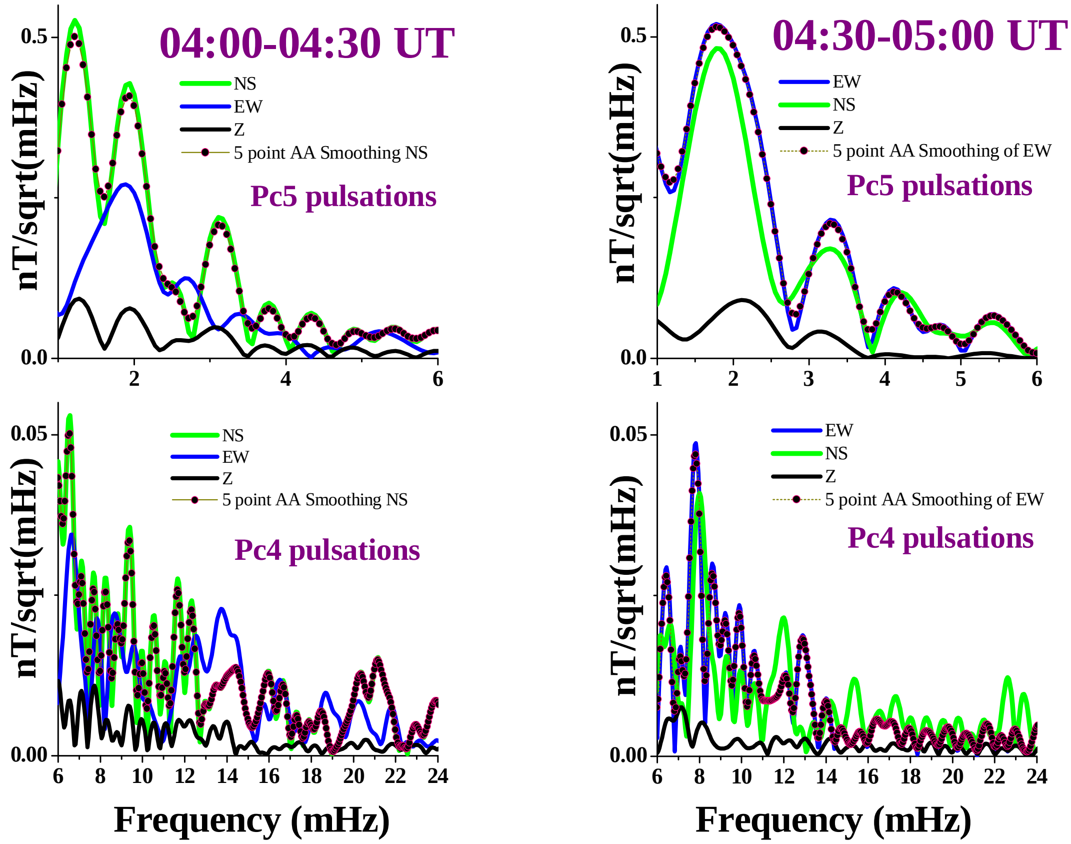

Fig. 2. Detection at LSBB site: Amplitude spectral density of the pulsations versus frequency, for the 3 components NS, EW and Z and the two time sequences, in the range 1–6 mHz (Pc5 pulsations top panels) and 6–30 mHz (Pc4 pulsations bottom panels). The dotted green lines, concerning NS show the similarity with the results of the polar station in the X direction shown in Fig. 1. The smoothing with 5 adjacent points averaging (pink dotted lines on NS and EW, respectively) shows that the Pc4 pulsations are not in the background noise.

(04:30–05:00 UT) four main frequencies, roughly in phase for the 3 components, are at 1.79 mHz, 3.25 mHz, 4.18 mHz, and 5.40 mHz.

To summarize, among the 9 pulsations identified in the sequence 1 spectrum, the three frequencies of the polar stations are present, with slight shifts of the 2 first frequencies. Besides, in the time interval 04:30–05:00 UT (sequence 2), the four wide resonances are in very good agreement with those of the polar stations in Manninen et al. (2010). This point will be discussed further.

Then we note that the LSBB spectrum reveals all frequencies recorded at different stations over the two time intervals. This consistency shows the full detection of magnetospheric and/or ionospheric signals with the SQUID[2] instrument in the underground low noise site of the LSBB because, as we are in near field regime, we have enough sensitivity. In addition with this similarity with polar detection, the signals on the EW and Z components exhibit some peculiarities: at the given frequencies, the maximum amplitude of the signal coincides for all components in sequence 2, which is not the case for sequence 1. The progressive modification in time of the EW signal will be seen further (in Fig. 5) and is analogous to a de-phasing between components.

As well, a fine structure of resonances is identified in the Pc4 band, up to 25 mHz, as seen in Fig. 1 (bottom panels) for the 2 sequences. A set of distinct lines is evidenced, not included in the background noise: when smoothing with 5 adjacent points, the average line discriminates each maximum of the spectrum (pink dashed lines on NS and EW in Fig. 2). It has been verified that the peaks are significant of the event as they are higher than the upper 95 % confidence interval of the mean. In sequence 1, some pulsations match for NS and EW components (for example at 8.3 mHz, 9.3 mHz, 16.0 mHz, and 21.2 mHz) or do not agree (at 6.5 mHz, 11.6 mHz, 17.5 mHz, and 26.7 mHz). In sequence 2, the frequencies are different, but generally correspond for NS and EW; however, common frequencies for the 2 sequences are rare (around 6.5 mHz, 9.4 mHz, 10.5 mHz).

The IMAGE stations in Fig. 1 are between 107° to 110° geomagnetic longitude, while LSBB is at 80.94° E longitude. Let us refer to polar stations with geomagnetic longitude in the range 81°–86°, near the LSBB longitude as seen

Fig. 3. Map of the polar stations with geomagnetic longitude in the range of 80°–86° (SOL, KAR – orange triangles and LSBB – green star) and in the range of 107°–110° (SOR, IVA, SOD and TAR stations – pink circles).

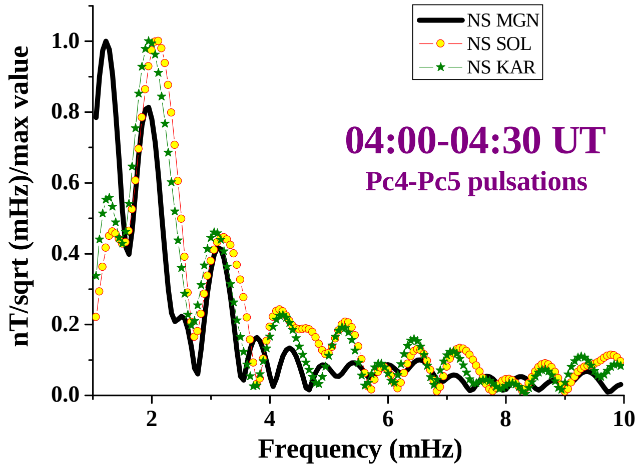

Fig. 4. Frequency spectra obtained from magnetograms of the three stations with comparable longitude, SOL, KAR and MGN-LSBB, in the range of 1–6 mHz, for the NS component (sequence 1). To normalize the results, the values are divided by the maximal value at each station.

in Fig. 3, for example Solund (SOL) and Karmoy (KAR), CGC 58.53° N latitude, 86.26° E longitude and 56.43° N latitude, 85.67° E longitude, respectively. The normalized resonance values from recordings at the three co-longitude stations, SOL, KAR and MGN-LSBB are shown in Fig. 4 for NS component in sequence 1: they are obtained by dividing the ASD values by the maximal value at each station. Three peaks with frequencies around 2, 3 and 4 mHz present very close values. Slight differences exist for the EW and Z components (not shown here) and the Pc4 pulsations are also similar (presented here up to 10 mHz).

4 Characteristics of the Pc5 pulsations

More precise characteristics of the waves associated with the Pc5 pulsations are obtained by filtering around each frequency. For illustration, in Fig. 5, the frequencies at 1.2 mHz and 1.9 mHz reveal a partial polarization of the signal components. The two pulsations are present in the two sequences (top left and right panels). In sequence 1 the EW signal is lower than the NS signal; this is different in sequence 2: around 05:00 UT the EW signal greatly increases. The Z signal is always about 1/4 of the NS or EW signals but it displays fluctuations in its amplitude which coincide with those of NS. This suggests the existence of a signal in this direction even of weak amplitude.

The signal at 1.9 mHz is also examined by filtering the data of the SOL station (Fig. 5 bottom panel) which is located at a comparable longitude but at a latitude higher than the mid latitude of MGN-LSBB. The wave features are in good agreement on the 3 components and do not present important phase difference (bottom panel). For the 2 time sequences, the coincidence between maxima and minima of each component at the 2 stations is not strict but very close (point to be noted as these stations are separated by more than 2500 km). Each type of waves can be analyzed on each component and compared with other stations. Here we don't propose such a study; we focus on the possibilities of such approach which brings information on the magnetic perturbations associated with the magneto-ionospheric events, but not on their origin.

Let us return to the fact that 9 pulsations are identified in the 04:00–04:30 UT-spectrum in the NS direction, while only four resonances exist in the time interval 04:30–05:00 UT. These 4 frequencies are in very good agreement with those of the polar stations revealed by Manninen et al. (2010). The 3 components show similar variation during this time interval (04:30–05:00 UT) (Fig. 2 right top panel). By continuity, we assume that these 4 main frequencies can be

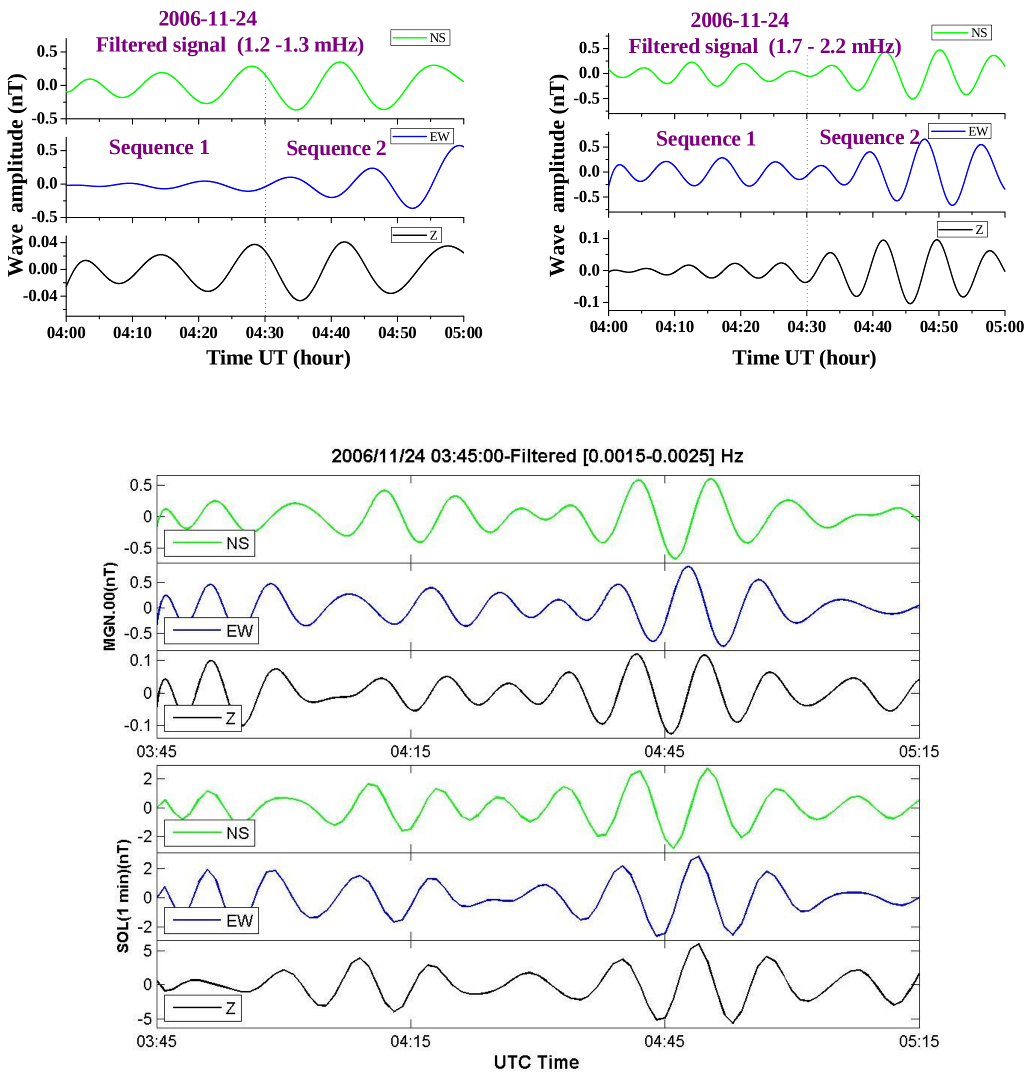

Fig. 5. Top panels: Features of the waves for two detected frequencies, around 1.22 mHz (left) and 1.90 mHz (right). Bottom panel: comparison between MGN-LSBB and SOL waves (from Intermagnet) at 2.00 mHz between 03:45–05:15 UT.

detected in the two consecutive intervals. Taking into account that propagating signals with close frequencies and amplitudes can interfere, the other resonances, only detected in sequence 1, may result from the combination of these main frequencies. So, the main pulsations at 1.91 mHz, 3.11 mHz, 4.31 mHz, and 5.39 mHz (detected at close values 1.79 mHz, 3.25 mhz, 4.18 mHz, and 5.40 mHz in sequence 2) can strictly present constructive beatings (their half sum) at 2.50 mHz, 3.72 mHz, and 4.87 mHz. All these values can be compared with the observed pulsations at 2.50 mHz, 3.75 mHz, and 4.88 mHz and we note the excellent agreement between the observed and calculated values, with a deviation less than 1 %. The pulsations at 1.22 mHz and 5.96 mHz could correspond to beatings between 2 other main frequencies, detected at 0.51 mHz and 6.51 mHz (shown in Fig. 6) out of the previously considered range of 1–6 mHz.

However, in sequence 2 (Fig. 6 right panel) we note that the pulsations are wide and we know from filtering (Fig. 5 top left panel) that the 1.2 mHz frequency (supposed to result from the beatings between the 0.51 mHz and 1.91 mHz frequencies) exists during the 2 sequences. The beating phenomenon, well visible in sequence 1, can be masked in sequence 2 by merging of frequencies, leading to the detection of only 4 frequencies at all polar or mid-latitude stations (in the range of 1–6 mHz). This interpretation is worth thinking about to analyze the detected signals. It can be said that when the different wave packets are not in coincidence (case of sequence 1) they may induce constructive beatings, while when they are in coincidence (sequence 2) the number of frequencies is arbitrary reduced by broadening of the lines. In consequence we observe a shift in the maximum of the amplitude spectral density, in agreement with our results. This

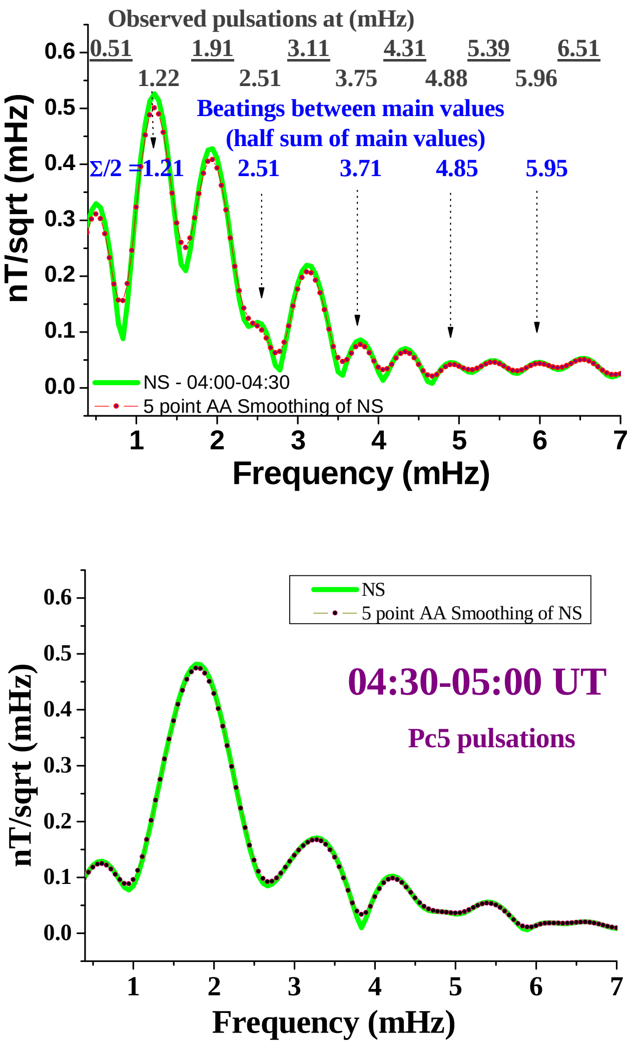

Fig. 6. Constructive beatings between main pulsations (underlined values) detected in the sequence 1 for the NS component. Only the main frequencies are present in sequence 2. The smoothing with 5 adjacent points averaging (pink dotted lines) is plotted in the figure.

behaviour is comparable with the behaviour of the 3.5 mHz pulsations which are in phase at ABK and IVA stations during sequence 2 but not during sequence 1, as presented in Manninen et al. (2010).

Concerning the origin of these waves, it is known that the ULF pulsation activity in the dayside magnetosphere is controlled by the solar wind speed. A significant knowledge of these waves cannot be obtained without analyzing the solar wind variations. On that date, a magnetic substorm with amplitude about 250 nT was observed at ∼02:00–04:00 UT and an energetic electron injection was recorded by geostationary LANL satellites before the event (Kleimenova et al., 2008). In the first discussed time interval, the solar wind dynamic pressure variations were turbulent and show oscillations in the large frequency range of ∼1.5–4.0 mHz. However, in the second interval spectra of the intensity variations demonstrated quasi-monochromatic oscillations. We can assume that the geomagnetic pulsations observed during the second time interval, represent poloidal magnetic variations (in the magnetic meridian) excited in the magnetosphere by the solar wind pressure oscillations. Then, in the first time interval (04:00–04.30 UT) it is probable that we observe the pulsations generated by the magnetic storm near the magnetopause boundary. Their propagation conditions from the auroral zone to the equator (Manninen et al., 2010) could induce the beating oscillations detected in this case. It is shown that these ULF pulsations have a significant magnetic component parallel to the ambient magnetic field.

5 Conclusion

The main result of this study is that the 3-D $[\mathrm{SQUID}]^2$ spectra obtained at mid latitude for the 24 November 2006 event between 04:00–05:00 UT show a very good agreement with polar stations spectra, between 1–6 mHz. The spectra are very comparable in the two time sequences (04:00–04:30 UT and 04:30–05:00 UT) and this point validates the observations of a magnetospheric event made at mid latitude and the identification of remote ULF sources in space with a single magnetometer in the underground low noise site of LSBB.

Moreover, due to the great sensitivity of $[\mathrm{SQUID}]^2$ and the quality of the environmental conditions, a rich magnetic activity is evidenced on this day: the full 3-D spectra exhibit resonant frequencies which can be identified up to 25 mHz, in the Pc5 and Pc4 frequency ranges. Analysis of the frequencies in the two sequences in the Pc5 range shows that all the vibrations can be regarded as main pulsations or induced constructive beatings due to the propagation of the waves. This phenomenon of beating frequencies is not evidenced at all polar stations but has been identified at SOL and KAR polar stations having similar longitude to that of LSBB.

To complete the analysis of these waves it is necessary to examine the orientation of these Pc5 pulsations and the detailed behaviour of the Pc4 frequencies; this study is on hand. This preliminary case-study shows that new experimental results can be expected in determining the propagation characteristics of the 24 November 2006 event wave packets by $[\mathrm{SQUID}]^2$ underground magnetometer, shielded against high frequency noise. In other cases, concerning for example atmospheric and magnetic storms or magnetic activity related to seismic events, detection and propagation of magnetic waves in the Pc5 band have also been recorded. The challenge is first to identify the spectra of each type of event and then to determine if the behaviour of the magnetic waves is event-dependent or not. The distinctive behaviour of the Pc5 waves associated with specific natural phenomena can be helpful in the understanding the Earth-ionosphere coupling through a magnetic survey, latitude-dependent. Of course a single instrument of this nature is not sufficient for a full space event characterization by its ULF magnetic signature. We are looking now for a worldwide network of several similar stations.

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