The ELF Band as a Possible Spectral Window for Seismo-Ionospheric Diagnostics

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Abstract. Parameters of the electromagnetic instruments employed at the Ukrainian Antarctic station (UAS) *Akademik Vernadsky* for data collection in the ULF-ELF band are described briefly along with the methodology of polarization processing. Spectral and polarization parameters of resonant Alfven oscillations in the ionosphere (10^{-1} - 10^{0} *Hz*) have been analyzed using the data of ELF electromagnetic monitoring at the UAS over the year 2006. As has been found, the discrete resonance structure of the ionospheric Alfven spectra is suppressed some time before a seismic event, to recover only hours later. Spectral parameters of Schumann resonances (10^{1} *Hz*) may also show an observable reaction to a distant earthquake, which manifests itself as a re-distribution of power of odd and even harmonics. The broadband ELF magnetic noise component that was present in one of the records changed its polarization a few hours before a distant quake and showed a behavior markedly different from the regular one. All this confirms the existence of seismo-ionospheric coupling, allowing us to observe earthquake precursory phenomena in the ionosphere over the epicenter.

Keywords: seismo-ionospheric, electromagnetic, ELF, Schumann resonator, Alfven resonance

Introduction

The study of *earthquake* (EQ) precursory effects, especially in the ionosphere above the region of an EQ under preparation, has resulted recently in more and more experimental facts to confirm the reality of such phenomena. Having no possibility to give references to all papers and monographs on the subject, we will limit ourselves here to some recent findings showing modification of the ionosphere above the focal area of a future EQ, as detected in studies of propagation of natural *electromagnetic* (EM) emissions in the *extremely low frequency* (ELF) band. The effect was reported for the first time in [1]. An ELF receiver located in Japan regularly recorded anomalous effects in the fourth *Schumann resonance* (SR) mode prior to EQs at Taiwan. This was explained by a very special configuration of positions of the American center of thunderstorm activity (source of the ELF oscillations), the Japanese SR monitoring station and the Island of Taiwan. The latter admittedly served as a resonant reflector for the fourth SR mode. The results of a better statistical validity obtained in long-term observations at the Kamchatka Observatory in Russia [2] also confirmed the appearance of parameter changes in ULF-ELF emissions at the preparation phase of a nearby EQ. Among other reasons, these effects were also interpreted as a result of SR activity redistribution owing to the EQ preparation. Thus, the ULF-ELF band seems to be most favorable for observing EQ-correlated effects, mainly because the background of natural emissions in the band is rather low and because the emissions themselves may serve as EQ precursors.

This paper describes the results of special processing of the data collected during long-term monitoring of the natural EM activity in the ULF-ELF band, aimed at identifying possible EQ-related effects in the morphology of such signals. The observations were carried out at the *Ukrainian Antarctic Station* (UAS) *Akademik Vernadsky* in the electromagnetically quiet region of the Antarctic Peninsula.

Experimental instrumentation

The UAS (former British station *Faraday*, L ~ 2.4; $65^0 15^{/}$ S, $64^0 16^{/}$ W) is equipped with high-class experimental instruments for the study of weak EM signals in the frequency band from *d.c.* to ~ 100 *Hz* [3]. The electromagnetic detectors include:

- two automated three-component fluxgate magnetometers LEMI-008 for the *d.c.* magnetic field;
- a set of five induction magnetometers LEMI-112 for measuring magnetic field variations;
- a two-component electrometer for telluric field measurements;
- an observatory system for data collection, timing and storage.

All the devices and the pertaining software have been developed and manufactured at the Lviv Center of the Institute of Space Research (LCISR), Ukraine. Considering the extremely low level of the natural EM noise in the region and the practical absence of man-made noise there, a special design of the magnetic sensors for observation of field variations at ULF-ELF had been suggested, to bring their own noise level as low as possible. The novel method for optimizing parameters of induction coil magnetometers [4] has allowed manufacturing the LEMI-112 magnetometers with parameters as follows:

- frequency band of measured signals: 0.3 to 300 *Hz*;
- magnetic noise level: ≤ 0.03 *pT Hz* $^{-1/2}$ at 10 *Hz* and ≤ 0.015 *pT Hz* $^{-1/2}$ at 100 *Hz* ;
- transformation factor at the principal differential output: 200 *mV/nT*;
- dimensions: 870 *mm* X 85 *mm*;
- mass: 5.6 *kg*.

These magnetometers were installed at the UAS in 1998 and have operated till the present time under the severe Antarctic conditions without any impairment, which is a solid confirmation of the design reliability. The EM monitor at the UAS is an integrated, synchronously operating data collecting system which has demonstrated its high reliability, as well as quality of the data through many years of permanent operation [5].

Monitoring Results

Spectral and polarization properties of the electromagnetic noise detectable in the range of 10^{-1} to 10^{1} *Hz* are widely studied for two reasons. On the one hand, the natural ELF radiation originating in the magnetosphere and atmosphere forms the background against which seismic-related signals are to be detected. On the other hand, parameters of the ELF waveforms themselves may bear the imprint of seismic activity, which effects are of special interest at the preparation stage of an earthquake [2, 6]. The structured waveforms observable in the UAS records of 2006 belonged to Schumann resonances, ground signatures of the IAR (ionospheric Alfven resonant oscillations), and Pc1 pulsations at the lower-frequency edge of the registration band. Our interest was centered at signals of the two former types which were studied for all seasons, periods of the day, and various geophysical conditions. This analysis has permitted a better insight into the diurnal and seasonal variations of the IAR parameters. Similar as at middle latitudes of the Northern hemisphere [7, 8], the resonant structure of the ELF waves was detectable in Antarctica mainly in winter time, from late evening till morning hours. On several occasions the IAR demonstrated an enhanced stability, when discrete resonance lines could be detected for a few successive days. Such records were characterized by low numbers of the resonances (no more than 3 to 5) with a considerable frequency difference (over 1 *Hz*) between them. Normally, both the number of discrete lines and the relative detection frequency showed depressions (often as low as total disappearance of the effect) between 14 and 16 or 17 *hr Local Time* (18 and 20 to 21 *UT*). This trough in the IAR intensity can be clearly seen in the upper panel of Fig. 1 showing the dynamic spectra of the signal intensity *I* on two dates of September, 2006 (the magnitudes represented in the other panels will be discussed below).

The intervals of signal absence are slightly different for each of the dates and, of course, shifted from the average values quoted above. The spectral lines are not uniformly spaced in frequency. Besides, the frequency difference ΔF shows a distinct diurnal variation, characterized by a maximum near 12 *hr UT*. This behavior of the IAR spectral lines was reported in all prior publications as typical for quiet ionospheric conditions. It was also stated that variations of the resonance parameters demonstrated a negative correlation with the electron density N_e in the *F*-layer [9]. The simple theory using the model of a constant Alfven velocity V_A and a uniform resonant volume of size *L* leads to a $N_e^{-1/2}$ dependence (as well as equal separations between the resonant frequencies [6, 7]). In actual fact the dependence upon the *F*-layer critical frequency (i.e. on N_e) shown by the IAR detection probability and other parameters is definitely non-monotonic, which can be seen, for example, in Fig. 2. Besides, the observable characteristics of the IAR are not controlled by f_{0F} alone but also by effective altitudes of the *E* and *F* layers, height profiles of collision frequencies, and parameters of the 'Hall layer' which determine the impedance Z_{eff} of the cavity's lower boundary. Assuming a linear run for the height dependence of V_A in the upper ionosphere (i.e., a constant gradient of the velocity),

$$\frac{V_{AJ}^2}{c^2}\left(i\cdot\frac{4\pi\sigma_\perp(\omega,z)}{\omega}\right)=\gamma(y_J-y)+1, \tag{1}$$

we can write closed-form solutions for the MHD wave equations in the IAR, and a dispersion relation which yields a non-uniform spectrum of the resonator eigenfrequencies [10],

$$Bi'(-\gamma^{-2/3})+i\frac{V_{AJ}}{c}\gamma^{-1/3}Z_{eff}Bi(-\gamma^{-2/3})=0. \tag{2}$$

Here $y=\frac{\omega}{V_{AJ}}z$; ω is the operating frequency; z the coordinate along the vertical; $\gamma\frac{\omega}{V_{AJ}}$ the slope factor in the linear dependence $V_A = V_A(z)$; $z = z_J$ the upper edge of the Hall layer (and $V_{AJ} = V_A(z_J)$), and $\sigma_\perp(\omega,z)$ is the transverse (Pedersen) conductivity of the plasma. In

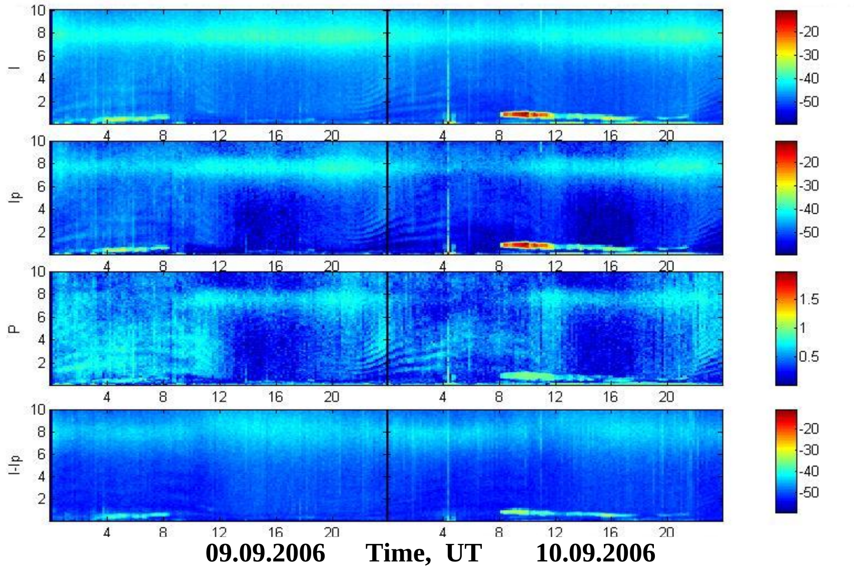

Fig.1. Dynamic spectra of the total intensity I, polarization ratio P, and intensities I_p, and $I_N = I - I_p$ of the polarized and non-polarized components, respectively, of the radiation in the range of IAR - ionospheric Alfven resonances. The records were taken at Galindez Island, Antarctica on (09-10).09.2006 . The broad line about 8 Hz belongs to the first Schumann resonance mode; the pattern of drifting discrete lines below represents ground signatures of the Ionospheric Alfvén Resonances.

view of $\frac{V_{AJ}}{c} \ll 1$, solutions of Eq. (2) should be close to the zeroes of $Bi'(-\gamma^{-2/3}) = 0$, where *Bi (x)* denotes the Airy function.

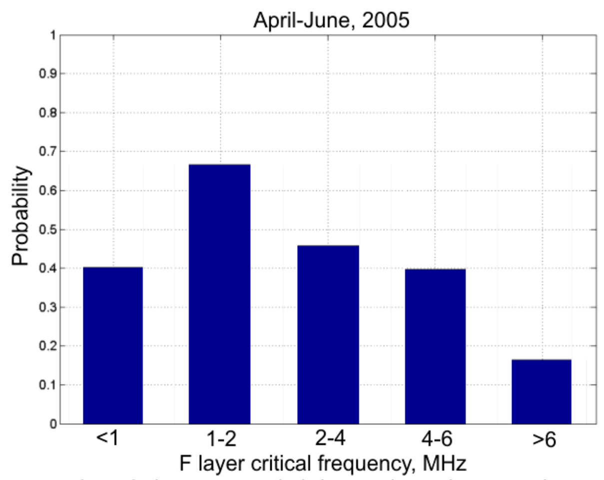

Fig. 2. The IAR detection probability in dependence on the F-layer critical frequency.

Polarization Properties of Ionospheric Alfven Resonances

The horizontal-plane magnetic vector of ELF waves, relating either to the IAR or the Schumann resonance field, generally shows an elliptic polarization. The polarization properties of Schumann resonances were studied by the present authors earlier [11, 12], and some of the results have proven useful for the analysis of seismicity-related emissions. The elliptic polarization of the IAR ground signatures is analyzed here, based on measurements of the *H* and *D* magnetic field components at Galindez Island ($65^0 15'$ S, $64^0 16'$ W) in 2006. The raw data recorded from two orthogonal channels (NS and EW) were processed in two stages. First, the 24-hour records were broken into10-minute intervals for which current spectra, S_{xx} and S_{yy}, and cross-spectra, S_{xy}, were estimated according to

$$S_{ik}(f) = \frac{1}{N}\sum_{p=1}^{N} \tilde{H}_i^{(p)}(f)\tilde{H}_k^{(p)*}(f), \tag{3}$$

with $i, k = x, y$. The subscripts x and y stand for the NS and EW directions, respectively. The ‘instantaneous’ complex spectra $\tilde{H}_{i,k}^{(p)}(f)$ of the field amplitudes, specified for time intervals $(p-1)T \le t \le pT$; $p = 1,2,...N$, were calculated from

$$\tilde{H}_{i,k}^{(p)}(f) = \frac{1}{T}\int_{(p-1)T}^{pT} dt H_{i,k}(t) e^{-i2\pi ft}, \tag{4}$$

which provides for a frequency resolution of 0.1*Hz* ($T = 10$ s). During stage two, the S_{xx}, S_{yy}, and S_{xy} spectra were used for polarization processing which was done for fixed frequencies within the $0.1Hz \le f \le 10Hz$ band of analysis. The separation between the frequencies was $\Delta f = 0.1Hz$. Diurnal dependences on the ‘slow’ time *t* were calculated for the Stokes parameters

$$I \equiv S_{xx} + S_{yy}, \; Q \equiv S_{xx} - S_{yy}, \; U \equiv 2\,\mathrm{Re}\,S_{xy}, \text{ and } V \equiv 2\,\mathrm{Im}\,S_{xy} \quad (5)$$

at each of the frequencies. These were used to estimate the ellipticity ratio $r(t)$, orientation angle $\Psi(t)$ of the polarization ellipse, polarized component's intensity $I_p(t)$ and polarization ratio, $P(t)$, *viz.*

$$r = \frac{V}{\sqrt{Q^2+U^2} + \sqrt{Q^2+U^2+V^2}}, \quad (6)$$

$$\left.\begin{matrix} \sin(2\Psi) \\ \cos(2\Psi) \end{matrix}\right\} = \frac{1}{\sqrt{Q^2+U^2}} \left\{\begin{matrix} U \\ Q \end{matrix}\right., \quad (7)$$

$$I_p = \sqrt{Q^2+U^2+V^2}, \quad (8)$$

$$\mathrm{P} = I_p / I. \quad (9)$$

The intensity I_{np} of the non-polarized component was estimated as

$$I_{np} \equiv I - I_p. \quad (10)$$

As can be seen, the Stokes parameters *Q*, *U* and *V* become identical zeros for the non-polarized intensity Eq.(10), which implies equal magnitudes of the orthogonal field vector components and total lack of their correlation. The spectrograms of the polarized intensity, polarization ratio and non-polarized component of the ELF magnetic field measured in Antarctica on September 9 and 10, 2006 are shown in the three lower panels of Fig.1. They are representative of the late winter period. Some intervals in the lower frequency part of each panel, 0.1 *Hz* $\le f \le$ 1~1.5 *Hz*, are occupied by tracks from the short-period geomagnetic pulsations known as 'pearls'. These are not related to the IAR and generally do not show any features to demonstrate a day-after-day reproducibility (like pulse duration or moments of appearance). In the higher frequency part, the first Schumann resonance line is centered about 8 *Hz* and occasionally extends to as low as 6 *Hz* and as high as 10 *Hz*. It reveals a marked diurnal repeatability or, rather, persistence. The intermediate range, $1.5\,Hz \le f \le 6\,Hz$, fully belongs to the signals initially formed as MHD waves in the ionospheric Alfven cavity. Fig.1 clearly demonstrates advantages of the polarization-processing approach to the analysis of natural ELF emissions. While the first Schumann resonance near 8 *Hz* involves a polarized, as well as a non-polarized component which are of comparable (though not equal) intensities, the IAR signatures show a much higher degree of polarization. Accordingly, the spectra of the IAR's I_p and P are characterized by a sharper contrast of the discrete tracks against the background, compared with the spectra of the total intensity *I*. In other words, application of the polarization processing permits improving the signal-to-noise ratio. The polarization ratio P varies within $0.5 \le P \le 0.75$. The intensity I_{np} of the non-polarized component at $1.5\,Hz \le f \le 6\,Hz$ remains almost unchanged through the 24-hour interval, and discrete lines are absent in the lowest-lying panel. As for the polarized intensity, it rather should be considered separately for three distinct intervals:

i) from 00:00 UT till 13:00 UT (i.e. 20:00 LT to 09:00 LT), night and early morning hours;

ii) from 13:00 UT till 17:00 UT (08:00 LT to 13:00 LT), daytime hours;

iii) 17:00 UT till 24:00 UT (13:00 LT to 20:00 LT), dusk and late evening .

The discrete tracks associated with the IAR response are distinctly seen in sections *i)* and *iii)* of the dynamic spectra of I, I_p and *P*. The average frequency separations Δf between the tracks are noticeably greater over interval *i)* than through interval *iii)*.

The spectra of the ellipticity ratio, *r*, and orientation angle Ψ of the polarization ellipse (major axis) are given in Fig. 3 (data of September 9, 2006).

During the daytime (interval *ii*) the polarized intensity, the ellipticity ratio and the polarization ratio all fluctuate about zero values, while the orientation angle may demonstrate occasional jumps by 180^0 (see Figs.1 and 3). This is evidence for the pure stochastic, non-resonance character of the detected radiation, in agreement with the many prior reports on the absence of discrete IAR spectra in the daytime. Combining the fact of the high degree of polarization of the IAR field at night with the small fluctuations of its ellipticity ratio about the zero level, we arrive at the conclusion that the IAR signatures are polarized almost linearly. As for orientation of the polarization ellipse, note that the angle ψ lies within $60^0 \le \psi \le 80^0$ at interval *i)* and within $75^0 \le \psi \le 110^0$ at interval iii*)*. A quite similar orientation of the ellipse with respect to the meridian was reported by Molchanov et al. [13] who analyzed data from measurements at the Kamchatka Peninsula ($53^0 N, 157^0 E$). The point is practically antipodal to Galindez.

Thus, the spectral window between ≈ 0.3 *Hz* and 6 *Hz* seems convenient for round-the-clock monitoring of potential seismo-related signals. Indeed, the only regular waveform present in the band, namely the atmospheric (ground) signature of the IAR is readily identifiable owing to its characteristic polarization and diurnal run. By applying polarization-sensitive data processing, it should be possible to clear up the non-polarized channel for unimpeded analysis of signals of any different kind. On the other hand, deviations of polarization parameters from the 'standard' behavior established for the IAR might serve as tell-tale of appearance of either another type of radiation or some agent to modify the Alfven resonator.

The Behavior of ELF Spectra about the Antarctic Earthquake of August 20, 2006

To investigate the possibility of detecting seismicity-related electromagnetic effects at ELF, we made a search for recent earthquakes of magnitudes M>5 that might have occurred within a fairly close vicinity of the Antarctic Peninsula. The USGS List of significant earthquakes [14] suggested only one event of the category for the period of 2001 till present. The epicenter of a M=7.1 earthquake on 20 August, 2006 was 495 *km*, WSW away from Bristol Island, South Sandwich group in the Scotia Sea, at 61.023° S, 34.373° W. In an attempt of finding any kind of anomaly in the behavior of ELF electromagnetic fields, we analyzed the data available from the bank of processed and pre-processed magnetic records from Station *Vernadsky* at Galindez, covering the period of August 18 through August 22. With respect to *Vernadsky* the epicenter was about 1800 *km* toward NNE (Fig.4). The dynamic spectra of signal intensity and polarization parameters within 0 – 10 *Hz* are presented for these dates in Fig.5. The variations of the intensities I, I_p and I_{np} with time on August 18, August 21 and 22, and first half of August 19 may be recognized as typical, despite the fact that the geomagnetic conditions were not really quiet through the five days. However, a few hours before the seismic shock (03.41.47 UTC, August 20) and hours after the discrete tracks of the IAR disappeared and could not be seen even in the polarization ratio *P* which is normally characterized by the highest contrast of the signal against the background. The suppression of the resonance oscillations at the time of an earthquake was noted earlier by other writers (e.g., [6]). Meanwhile, the period preceding the quake demonstrated a broadband emission in the range of the IAR which is seen clearly in the spectra of both polarized and non-polarized intensities (note the pulses at ≈ 22 hr on August 19 and 2:30 UT on August 20).

A really remarkable spectral feature is detectable from 03:20 UT to 03:30 UT, August 20 (i.e. immediately before the quake) in the frequency range of Schumann resonances. Shown in Fig. 6 is a sequence of intensity spectra between ≈ 1 *Hz* and 25 *Hz*, taken for 10-minute time intervals from 03:00 UT to 03:50 UT. Spectacular is the sharp increase of the first and third Schumann resonance peaks in the spectrum for 03:20 to 03:30 UT, compared with all other periods. By analyzing one-dimensional spectra of all parameters it has been found that the anomaly manifests itself in I and the polarized intensity I_p. In the case of I_p the increase can be characterized by a factor of ~2.35 for the first Schumann peak and ~1.57 for the third mode. Besides, the first resonance frequency itself shifted during the anomalous period from the 'quiet' values of 7.8 or 7.9 *Hz* to as low as 7.6 *Hz*. At the same time the spectral amplitudes of the second and fourth resonances showed little if any changes (see Fig.6). Other polarization parameters, including the non-polarized intensity I_{np}, did not change either.

So, the question is whether the reported anomalous variations of the ELF spectra are related to the seismic event. We have considered two possible physical mechanisms of the anomaly. According to one of these, the magnetometers at the observation site might have fixed some additional electromagnetic emission arriving in the form of a ground wave from a source in the vicinity of the quake focus. The other mechanism stresses changed conditions for the propagation of the permanent background radiation in the Earth-ionosphere cavity which may result from seismicity-induced changes in the ionosphere. In the first case the electromagnetic radiation to arrive from the focal area should look like an additive contribution to the regular background, to some extent raising the spectral intensities at all frequencies. The spectral distribution of this addendum can be estimated from the considerations as follows. Because of the high

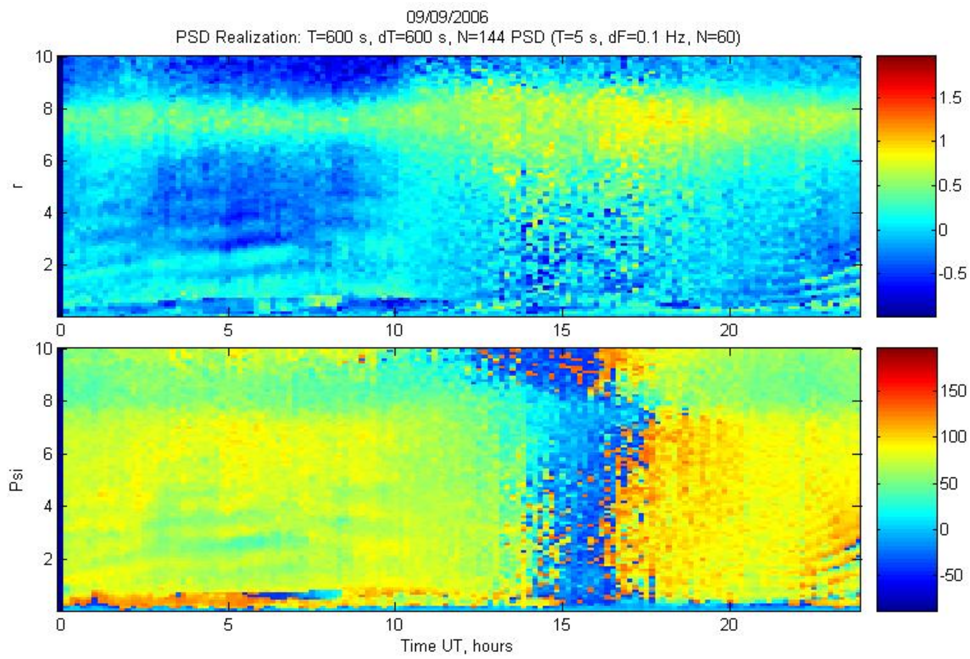

Fig.3. Dynamic spectra of the ellipticity ratio r and orientation angle Ψ of the polarization ellipse (ground-level magnetic component of the IAR, record of 09.09.2006).

conductivity σ of crustal rocks at ELF, the attenuation rate α of seismogenic radiation varies in the range like

$$\alpha(f) = (2\pi f / c)\,\mathrm{Im}\sqrt{\varepsilon' + i2\sigma / f} \approx (2\pi / c)\sqrt{\sigma f} \quad (11)$$

(ε' is the real part of the rock's dielectric constant).

This suggests a slow monotonic decrease of the addendum intensity, $I_{+} \sim \exp(-aL)$, with growing frequency. Evidently, such a dispersion law has very little in common with the selective enhancement of only odd-order Schumann peaks that has been reported.

In the other case parameters of propagational ELF fields coming from remote external sources are modified because of disturbances in electron density which may arise from seismo-ionospheric interaction. Possible physics of the interaction has been discussed in the literature (see [15] and references therein). As is well known, three centers of the world thunderstorm activity, lying in the equatorial belt, are principal sources of the natural electromagnetic fields belonging to the Schumann resonance range. The combined effect of the American, Asian and African centers upon the spatial structure and polarization of ELF noise was re-considered recently by some of the present authors [11, 12]. According to this analysis, Station Vernadsky is so located *vis-a-vis* the African center as to be in the zone of destructive interference for the fields of all even-order Schumann modes arriving from the center. The epicenter of the August 20 earthquake (South Sandwich Isles) can be seen to lie right on the great circle path connecting Vernadsky with the African thunderstorm center. Hence, by assuming that the earthquake had initially modified the local ionosphere above the epicenter, we are led to the conclusion that disturbances in the ELF spectra should not be seen in even-order peaks.

Next, we need to discuss the amplitude and frequency variations of odd-order resonances in

Fig.4. Positions of the observation site at Station Akademik Vernadsky and epicenter of the August 20, 2006 earthquake in Scotia Sea.

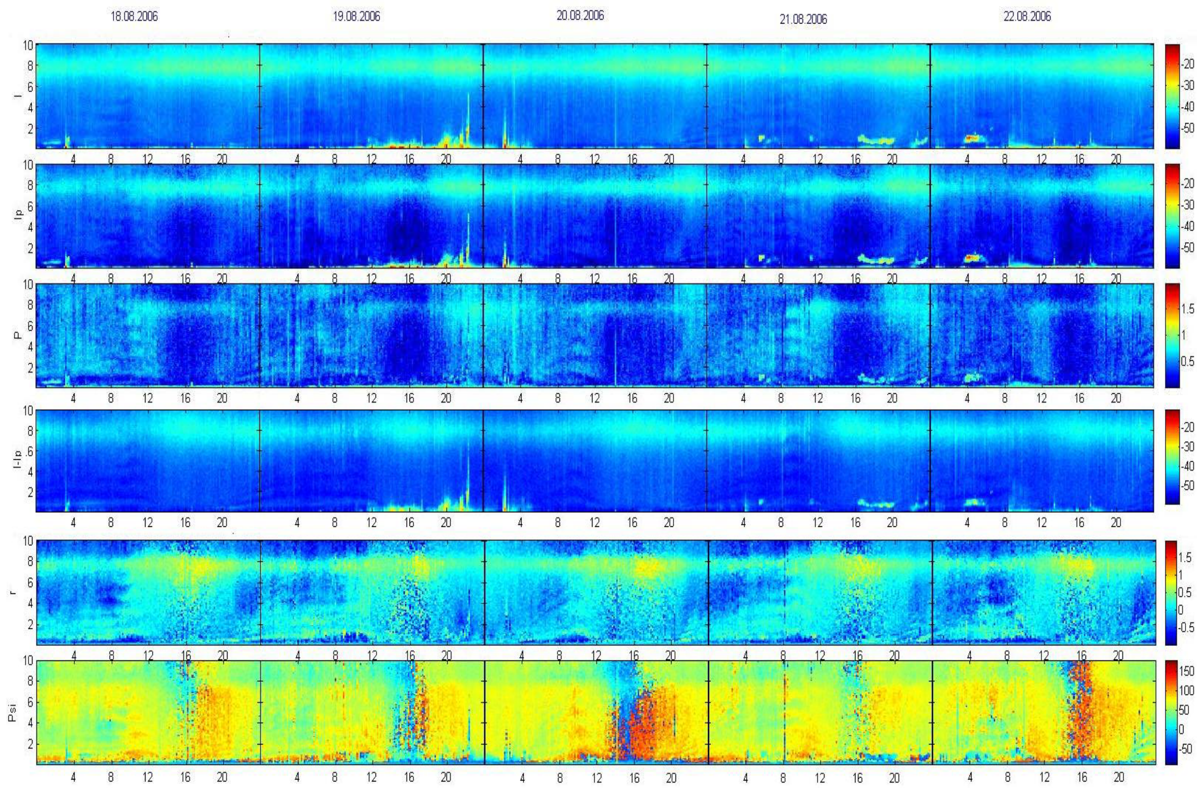

Fig. 5. Dynamic spectra of the signal intensity I and polarization parameters Ip, P, Inp , r and ψ recorded at Station Vernadsky on the dates about the Scotia Sea earthquake (the moment of shock, 03.41.47 UT, 20 August, 2006 is shown with a dashed line).

connection with the earthquake-induced changes of ionosphere parameters. As is well known [16, 17, 18], the effect of the ionosphere upon the field distribution in the Earth-ionosphere cavity can be described in terms of an equivalent height of a sharp ionospheric boundary and a surface impedance at that level. Assuming that an earthquake produces some additional ionization in the ionosphere, thus locally decreasing its effective height *h*, we can find from the theory that the resonance frequency should decrease as $\omega_n = \omega_{n0}(1 - \frac{c|Z|}{4h\omega_{n0}})$. Here $\omega_{n0} = \frac{c}{a}\sqrt{n(n+1)}$ is the *n*-th resonance frequency for the ideal cavity (perfectly conducting concentric spherical walls); *a* is the Earth's radius and *Z* is the ionospheric wall impedance. Accordingly, the field amplitude should increase. Thus, the sense of changes in both values is in agreement with the observations. However, these conclusions, no matter how favorable they may seem from the point of interpreting the above described measured result, are no more than indicators of a qualitative tendency. In fact, the theories quoted operate with global parameters *h* and *Z* of the cavity, while the earthquake-induced variations are localized to some vicinity of the epicenter. Besides, the relative magnitudes of measured variation are very different for the frequency and the amplitude, which cannot be explained within the rather simplified approach discussed here.

Conclusions

1. Horizontal-plane magnetic field components of the Ionospheric Alfven Resonance emissions are elliptically polarized, hence separation of the polarized and non-polarized components in the ELF signals below 10 *Hz* permits increasing the SNR for the IAR, while clearing the non-polarized window for detection of possible seismicity-related signals of different nature.
2. Analysis of spectral and polarization parameters of the IAR over a time period including a remote earthquake showed that the discrete resonance structure of the IAR spectra was suppressed shortly before the seismic event, not to be recovered until hours later at night.
3. Spectral parameters of Schumann resonances showed a distinct reaction to a remote earthquake, demonstrating a 30 % increase in the amplitude of the first resonance mode with a 4 % downshift of the frequency some 15 or 20 minutes before the seismic shock.
4. The broadband component of ELF noise detected a few hours before the quake showed a magnetic polarization markedly different from the 'normal' noise and resonance fields in the 10^{-1} - 10^{1} *Hz* range.

Acknowledgments

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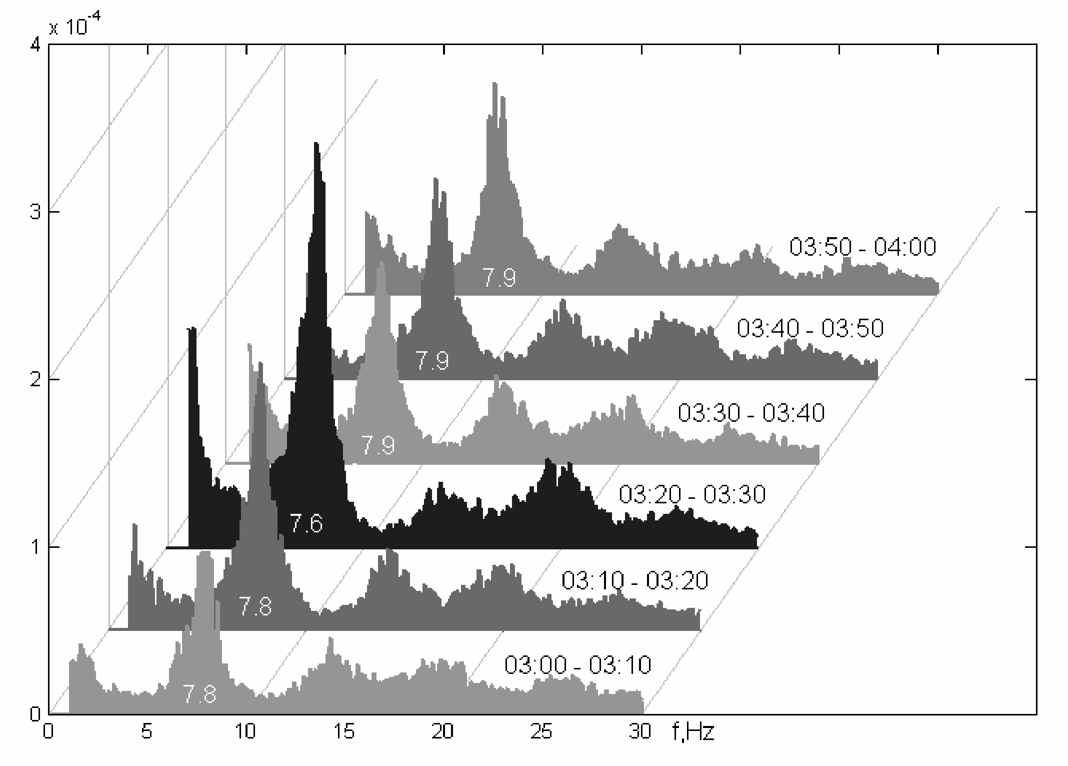

Fig.6. Successive spectra of ELF field variations in the range of Schumann resonances measured at Station Vernadsky, Galindez Island on the night of the August 20 earthquake.

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