EM monitoring of the Earth's interior and the nearest space environment

EUGENE A. KOPYTENKO, VALERI S. ISMAGUILOV, YURI A. KOPYTENKO
St.Petersburg Branch of Institute of Terrestrial Magnetism Ionosphere and Radiowaves Propagation
Russian Academy of Science
Muchnoj 2, St.Petersburg 191023, Box 188,
RUSSIA
Eugene@ek5666.spb.edu Yuri@yk5665.spb.edu

ANDREY L. KOTIKOV
Earth Physics Department
St.Petersburg State University
Ulyanovskaya Str. 1, Petrodvoretz, St.Petersburg 198504,
RUSSIA
Andrey.Kotikov@paloma.spbu.ru

KATSUMI HATTORY
Chiba University, Chiba
JAPAN
hattori@earth.s.chiba-u.ac.jp

MASASHI HAYAKAWA
The University of Electro-Communications
1-5-1 Chofugaoka, Chofu Tokyo 182-8585
JAPAN
iwse2005@whistler.ee.uec.ac.jp

Abstract: - The ULF EM (Ultra Low Frequency Electromagnetic) emission's source location method is applied to monitor the behavior of the sources of different origin. The approach is based on the use of magnetic gradiometer. Three portable high sensitive magnetic stations are deployed at the distance of about 5 km apart. During active ionospheric experiment around Tromso (Norway) the magnetic effect from the luminous spot at the height of about 100 km produced by energetic particles of field aligned currents was detected and monitored by ground based gradiometer and all sky TV camera. The possibility to resolve spatial and temporal variations of auroral phenomena was pointed out. Two magnetic gradiometers were installed in seismic zone around Tokyo. Anomaly behavior of gradient and phase velocity vectors of ULF (F<1 Hz) geomagnetic disturbances were investigated for two earthquake events in Japan in 2000 (M>6) and 2003 (M=5.8). It was found that the values of the gradient and the phase velocity have anomaly changes 3-6 months before the strong earthquakes.

Key-Words: - magnetic gradiometer, ULF electromagnetic emissions, ionospheric currents, earthquake source location

1 Introduction

Since 1957, The First International Geophysical Year, scientists from different countries started to use magnetic instruments with the aim to monitor Earth's interior and atmospheric phenomena. The requirements in precise magnetic measurements used in field conditions were motivated by rapid development of different geophysical methods for academic research and mineral prospecting and for military needs. A number of research teams reported about designing numerous types of magnetic transducers. Some of them were capable to resolve extremely weak magnetic field variations. Nuclear precession, optically pumped, fluxgate, induction coils, cryogenic (SQUID) and torsion type of magnetometers played a main role in applied magnetometry.

The scientific progress in the last decade of previous century was tightly bonded with significant success in computer science, microelectronic and space technologies. Recently almost no one of portable geophysical instrument doesn't use GPS system in its operation. All these accumulated facts allowed to plan and to carry out complicated programs and experiments that had been fantastic even twenty years ago. Self consistent or temporal observations of ULF electromagnetic field from carefully installed geophysical networks have lead to answers on many fundamental questions about the origin of the ULF electromagnetic emission.

In this brief report we'll concern the topic of simultaneous multipoint observations of ULF electromagnetic fields aimed to locate its sources.

2 Brief description of the method for location geomagnetic ULF emissions sources

2.1 Common reasoning

It is well known that subsurface geoelectrical inhomogeneities essentially disturb natural electromagnetic field observed at the ground [1]. In particular, amplitudes and phases of geomagnetic ULF emissions (geomagnetic pulsations) registered simultaneously at the number of observation points around region with anomaly conductivity can have significant differences when the dimensions of inhomogeneity are equal to the wave length of the ULF emission. Traditional methods of studying geomagnetic pulsations in frequency range 0.001 – 1 Hz suppose multipoint observations with stations spaced apart 100 – 150 km along or across meridian [2], [10]. It is obvious, that if the magnetic gradiometer will have base length less then linear dimensions of the representative anomaly we can calculate gradients and phase more accurately. Of course, the assumed distance to the located source shouldn't exceed 10 – 20 times the base value. Otherwise, the method will lose its sensitivity. Taking into account the reasoning mentioned above we chose 5 - 7 km base length for the deploying magnetic gradiometer. By placing the instruments as a triangle it is possible to cover (to monitor) the area with the radii of about 150 km while using standard portable field instruments.

2.2 Description of the instruments

The quality of the experimental material is the background for the future conclusions. Modern magnetometric systems have tremendously high dynamic range, good linearity in a whole frequency band, small dimensions and low power consumption. As to magnetic sensor there is no huge array of portable instruments for measuring weak magnetic variations in ULF range. The researchers should focus at tree types of magnetic sensors: induction coil, fluxgate and torsion type of magnetometers. The choice will depend on the experiment conditions. The accuracy of the gradient method calls for high precision clocking system used in data logger, small dimensions and easy operation as well. In the end of 90th new magnetometric system (Magneto Variation Complex – MVC) was designed in SPbF IZMIRAN on the base of torsion type magnetometer [3]. Continuous elaboration of magnetic sensor and data acquisition system of MVC allowed to create portable field station capable to resolve time intervals not worse then 50mksec with the sensitivity in magnetic channels of about 2pT. Frequency range of magnetic sensor is 0 to 10 Hz. These advantages belong to MVC-2DS and MVC-4DS both magnetotelluric systems, that were used in experiments.

Fig.1 MVC-4DS - portable magnetotelluric station

The only difference between two instruments is the type of data collecting PC. MVC-4DS has a build in industrial PC in form factor PC104 and a flash Hard Drive to diminish weight and risk of damaging while transporting the precise instrument. Both Data Acquisition Systems based on 24-bit Analogue to Digital Convertion sigma-delta modulation technique have build-in GPS board to tie up samples with Universal Time.

2.3 Background for the estimation of magnetic gradients from natural EM ULF emissions

Basic argument of the method is an assumption that the front of the geomagnetic pulsation wave can be considered as a plane one. Indeed, it is a quite realistic fact, when the distance between magnetic stations used in gradiometer is much smaller then the distance to the ionospheric source of geomagnetic pulsations. Therefore, the values of the pulsation's amplitude along the wave front will stay constant, and the phase delay between any two points on the front will be equal to zero. The arrival time of the wave front can be precisely determined by specific peculiarities of geomagnetic field pulsations at any of the three gradiometer magnetic stations. Then the propagation velocity of these waves along the earth surface and the gradients of the amplitudes each of three mutual orthogonal components of geomagnetic pulsations can be calculated. After determining the direction of the geomagnetic pulsation's wave propagation and the direction of the magnetic gradient's vector, we can locate the ionosphere source of geomagnetic pulsations relatively to gradiometer's position.

In our consideration we assume that all three stations lay in the plane, other way the difference in their elevation is neglectable. One station is chosen as a reference. Below in the text it will be called a station with index 1. Using gradiometer's data it is possible to calculate the direction to the geomagnetic wave source along the earth surface at any moment by two independent techniques [4].

First approach uses phase delay between similar wave packages:

$$tg(\alpha) = \frac{(y_3 - y_1)t_{12} - (y_2 - y_1)t_{13}}{(x_2 - x_1)t_{13} - (x_3 - x_1)t_{12}} \qquad (1)$$

where $x_1, y_1, x_2, y_2, x_3, y_3$ - coordinates of three magnetic stations of the gradiometer; $t_{12} = t_2 - t_1$, $t_{13} = t_3 - t_1$ - time delays of the geomagnetic pulsation's wave front arrival to magnetic stations **2** and **3** relatively to the base station **1** at the moment t; α - angle between the direction to the geomagnetic north and the direction of the wave front propagation from the source.

Second approach uses differential values of geomagnetic pulsation's components determined by the data of the gradiometer's measuring:

$$tg(\beta) = \frac{(y_3 - y_1)\Delta B_{12}(t) - (y_2 - y_1)\Delta B_{13}(t)}{(x_2 - x_1)\Delta B_{13}(t) - (x_3 - x_1)\Delta B_{12}(t)} \qquad (2),$$

where $\Delta B_{12}(t) = B_2(t+t_{12}) - B_1(t)$, $\Delta B_{13}(t) = B_3(t+t_{13}) - B_1(t)$ – is the difference of the magnetic field induction values of geomagnetic pulsation components measured at magnetic stations **2** and **3** relatively to the base station **1** at the moment t, with phase delays t_{12} and t_{13}; β - is an angle between the direction to the geomagnetic north and direction of the geomagnetic field component gradient vector.

The geomagnetic pulsation sources of ionospheric origin have relatively small dimensions [5]. If we take into account a model of generation geomagnetic pulsation as a moving and pulsing footprint on ionosphere of magnetospheric field-aligned currents [6], then the gradients of the vertical component and the gradients of total horizontal component of the ULF magnetic disturbances will point to the center of ionospheric source of geomagnetic pulsations.

Velocity of the geomagnetic wave front propagation along the Earth's surface can be determined as:

$$\mathbf{V} = d_{12}\cos(\alpha - b)/t_{12} = d_{13}\sin(\alpha + c)/t_{13} \qquad (3)$$

Where

$d_{12} = ((x_2 - x_1)^2 + (y_2 - y_1)^2)^{1/2}$ - the distance between first and second observation points and

$d_{13} = ((x_3 - x_1)^2 + (y_3 - y_1)^2)^{1/2}$ – the distance between first and third observation points

$b = \arccos((x_2 - x_1)/d_{12})$; $c = \arccos((y_3 - y_1)/d_{13})$.

Angle α was determined in (1).

The gradient value of any of the magnetic field components on the earth surface, using (2), is determined as:

$$\nabla \boldsymbol{B} \approx \Delta B_{12}\cos(\beta - b)/d_{12} = \Delta B_{13}\sin(\beta + c)/d_{13} \qquad (4)$$

Angle β was determined in (2).

In our discussion we intentionally missed a problem about non collinearity of the sensitive axes of magnetic sensors deployed at the surface of the ground. Actually it is impossible to set up the instruments in proper direction without angular mistakes. Detailed consideration of this problem has been done in [7].

3 Application of the location method to monitor the natural EM phenomena

3.1 Investigation of ULF magnetic disturbances during heating campaign in march 2004

In March 2004 a complex geophysical experiment was carried out around EISCAT heating facility in Tromso. Experiment aimed to prove and systematize previously obtained results on effects in ionosphere-magnetosphere coupling during the HF heating [8].

Three identical 3-component high-sensitive torsion magnetometers MVC-4DS (SPbF IZMIRAN) were deployed at the North part of Finland (Kilpisjarvi) at the points of triangle at distances of 3.5 – 4.9 km apart. Such geometry of positioning the magnetometers allows to determine the magnetic gradients along the Earth's surface using a phase-gradient method [4]. Portable all-sky TV camera was set up near the Centrum of that triangle to monitor Aurora.

Figure 2 plots the time dependence of four variables for 24-25 March 2004 experiment in Kilpisjarvi (Finland):

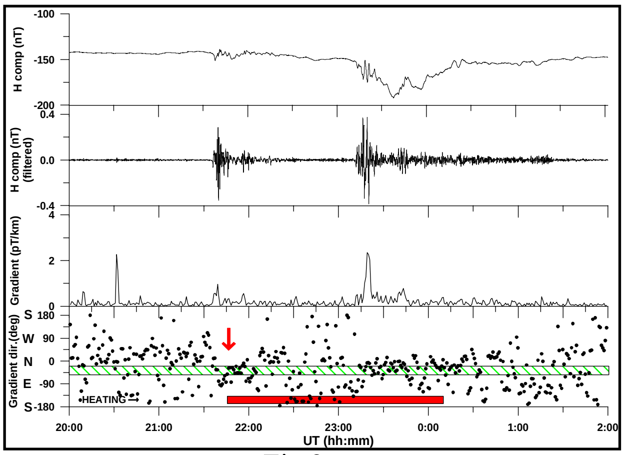

Fig.2

1. H – horizontal component of the magnetic field, measured at one of the magnetic gradiometer's observation point
2. The same H – component filtered with BPF 0,03 – 0,01 Hz
3. Value of the horizontal magnetic gradient

4. An angle between direction to the north and gradient vector direction

Anomaly effects in amplitudes and gradients of the ULF geomagnetic variations were observed in a wide frequency range (f = 0.001 – 0.2 Hz) during the ionosphere heating. It was found that the amplitudes and gradients values of the geomagnetic variations were increasing while heating was in progress. During the experiment the direction to the most significant magnetic source, that was calculated using gradient methodic had a significant dispersion before and after ionospheric heating. However, during the heating time interval a decrease in dispersion was observed, while the gradients vectors were mostly directed to the Tromso HF transmitter (dashed sector at lower panel at figure 2).

On March’24 it was the only case when successful registration of Aurora with digital all-sky TV camera was carried out simultaneously with other observations and operating HF transmitter. Figure 3 represents the time dependence of the absolute value of the gradient of ULF magnetic field dG in horizontal plane and an angle ά, where ά is the angle between geographic North direction and direction of the ULF magnetic field gradient in the horizontal plane for the 12 minutes time span 23:19 – 23:27 UT.

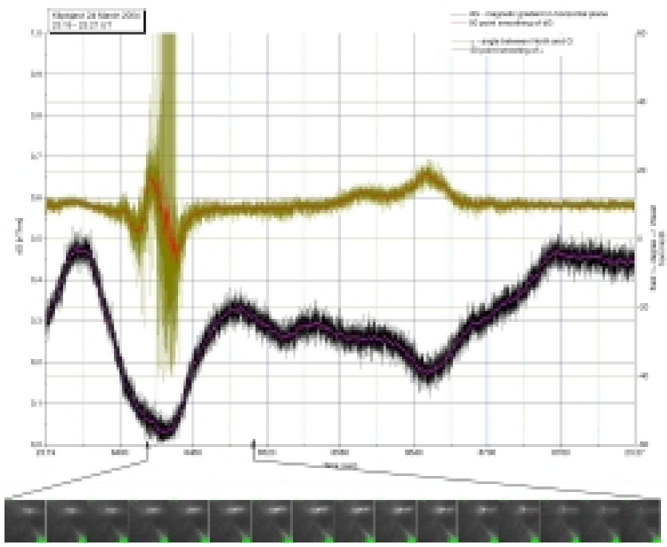

Fig. 3

The set of snapshots from all-sky TV camera, processed according to the technique developed in [9], are plotted at the bottom part of the figure 3. One can see that the dynamic of the absolute value of gradient of magnetic field variations and an angle ά are followed by the aurora luminosity. Moreover the IRIS riometer data identify an increase in riometer absorption exactly in the beam that is projecting on the ionosphere spot of the HF transmitter beam.

In conclusion it is necessary to emphasize the point, that the method uses only three instruments to locate the ionospheric sources of ULF emissions, while in experiment “BEAR” 1998 [10] the similar task was solved with 66 magnetotelluric stations placed in northern Scandinavia.

3.1 Determination of hearth position of forthcoming strong EQ using gradients and phase velocities of ULF geomagnetic disturbances

Continuous observations of the magnetic field variations and telluric currents in Japan at the Izu and Boso peninsulas have been conducted since 1998 by means of six high-sensitive digital three-component magnetic stations MVC-2DS (Fig.4). Each group of three stations represents a magnetic gradiometer. The magnetic stations in each group are spaced 4-7 km apart. The stars at the Fig.4 depict epicenters of the strongest EQs. Figures near the epicenters mean the EQ’s magnitude determined according to the JMA scale. The analyzed period with increasing seismicity started on 26.06.2000 and covered three EQs with M>6.0. The strongest seismic shock (M=6.4) occurred on 01.07.2000. Epicenter of this EQ was located at the depth ~15 km under the sea bottom at the distance of about 85 km southeast from the magnetic stations on Izu peninsula (Fig.4). The seismicity around Boso peninsula was rather active during the whole year 2003. The strongest seismic shock (M=5.8) occurred at the depth ~60 km and its epicenter was located about 15 km East from the magnetic stations location at Boso (Fig. 4).

An anomalous behavior of gradients and phase

Position of magnetic stations
and strong EQ epicenters in 2000 (M>6)
and 2003 (M=5.8) (Japan)

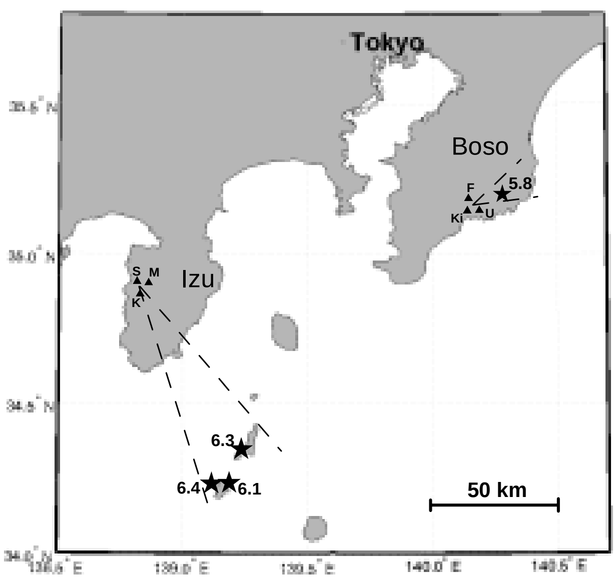

Fig. 4

Black triangles - three-component magnetic stations (S, M, K – Seikoshi, Mochikoshi and Kamo at Izu peninsula; F, Ki, U – Fudago, Kiyosumi and Uchiura at Boso peninsula).

velocities of geomagnetic emissions in the frequency range F=0.1-0.4 Hz in the region of Boso peninsula is demonstrated at the Fig.5. The moment of the strongest seismic shock is marked by a vertical dotted line. The gradients in the total horizontal component and in the vertical one were increasing during half of the year 2003 before the moment of EQ and reached their maximum 2-3 months before the EQ. At the same time the values of the phase velocities decrease and their minimal values were observed before the EQ moment. The similar anomalous behavior of the gradients and phase velocities is also observed in the frequency range (F<0.1 Hz) of the ULF geomagnetic disturbances. Unfortunately the data for July and August 2003 were lacking.

Time evolution of gradients and phase velocities of geomagnetic emissions (F=0.1-0.4 Hz) before and after EQ M=5.8 at Boso peninsula, Japan, 2003

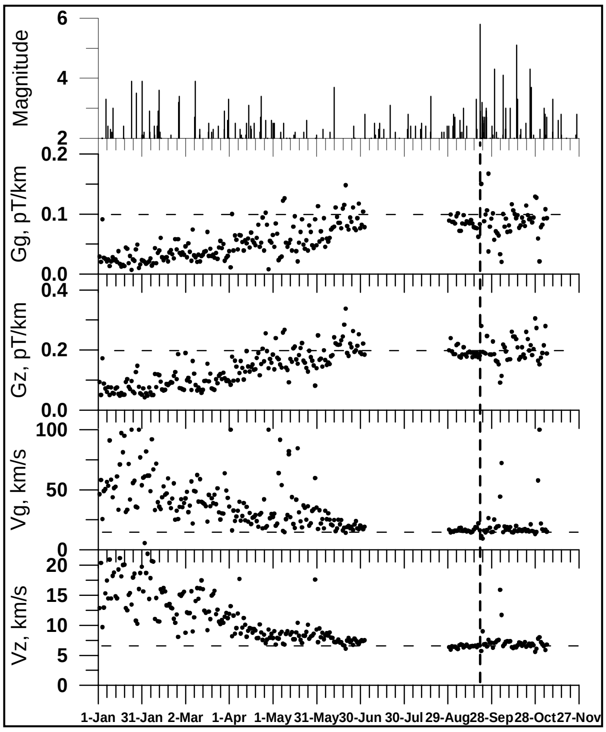

Fig. 5

V_g, V_z, G_g, G_z – phase velocities and gradients in total horizontal and vertical components of magnetic field. Magnitudes of seismic shocks (M>2) are presented at the upper part of the figure.

An anomalous behavior of gradients and phase velocities of the ULF geomagnetic emissions was also observed before the EQs near the peninsula Izu in 2000 and was published earlier in [11], [12], [13], [14].

Fig.6 plots the distributions of probabilities of gradient (left part of the figure) and the phase velocity vector directions (right part) of the ULF variations in the frequency range F=0.03-0.1 Hz (mean-month values) for the period January-October 2003. These histograms were constructed using total horizontal component calculated on the magnetic data collected at stations situated at Izu peninsula. At Fig.6 a distinct maximum in the distribution of directions of the gradient vectors appeared two – three months before the beginning of the seismic activity for the future seismic activity region only. Shaded vertical strip marks this direction. The strip corresponds to 30^o cone plotted with dotted lines in Fig.4. The vectors of the

Probability distributions (monthly mean values) of gradient (left) and phase velocity (right) vector directions of total horizontal component of ULF magnetic disturbances (F=0.03-0.1 Hz) before and after strong EQ (M=5.8), Boso peninsula, Japan, 2003

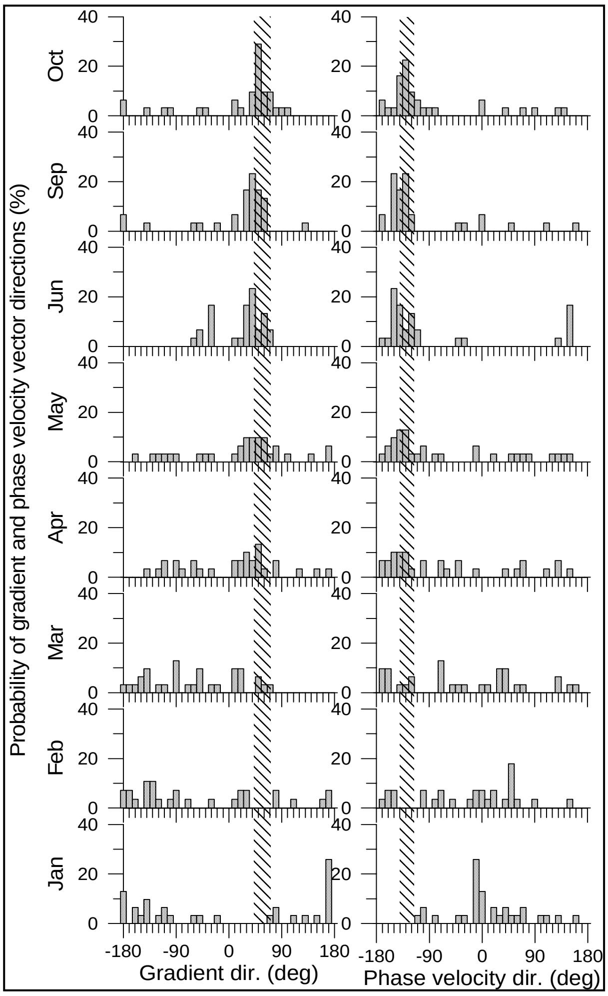

Fig. 6

Vertical dotted band corresponds to direction to the EQ epicenter (20.09.2003, M=5.8) for gradient and from the EQ epicenter for the phase velocity vectors. Direction to the north corresponds to 0^0, to the east – $+90^0$, to the south - $\pm 180^0$ and to the west - -90^0.

phase velocities are directed on the opposite side (out of the future seismic active zone).

Fig.7 demonstrates histograms of distributions of probabilities of gradient (left part) and the phase velocity vector directions (right part) of the ULF variations in the frequency range of F=0.03-0.1 Hz. Monthly averaged values are shown for the period February-July of 2000. These histograms were calculated using total horizontal components obtained at the Boso peninsula. At Fig.7 it is clearly seen that a direction to the region of a future strong EQ appeared 5-6 months before the strongest seismic shock with magnitude M=5.8. In Fig.7 this direction is marked by a shaded vertical strip corresponding to 30^o cone plotted with dotted lines in Fig.4 (Boso peninsula). As in the previous event, the phase velocity vectors point to the opposite direction in comparison with the gradient vectors.

Probability distributions (monthly mean values) of gradient (left) and phase velocity (right) vector directions of total horizontal component of ULF magnetic disturbances (F=0.03-0.1 Hz) before and after strong EQs (M>6), Izu peninsula, Japan, 2000.

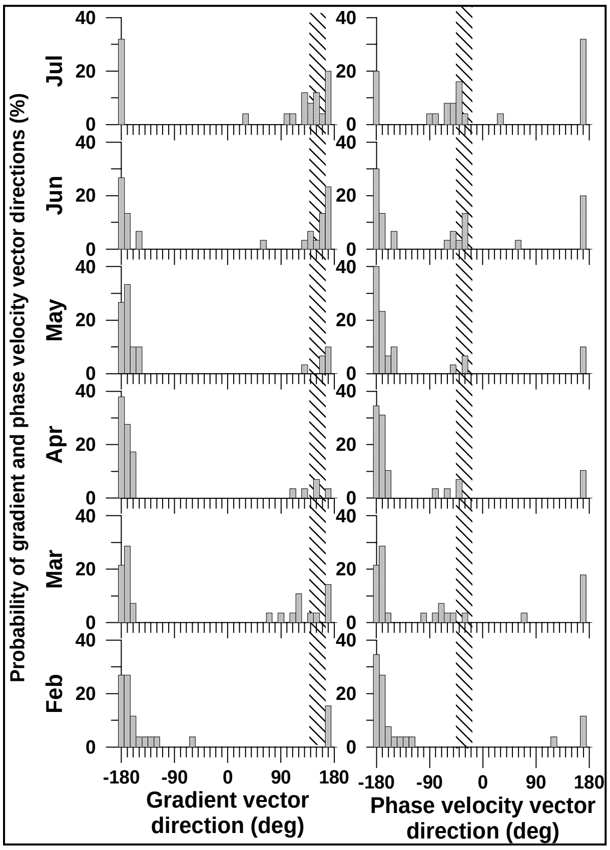

Fig. 7

Vertical dotted band corresponds to direction to the EQ epicenters (July 2000, M>6) for gradient and from the EQ epicenter for the phase velocity vectors. Direction to the north corresponds to 0^0, to the east – $+90^0$, to the south - $\pm 180^0$ and to the west - -90^0.

In the Fig.6 the EQ moment with magnitude M=5.8 is marked by a vertical dotted line. We can see at the figure that about 6 months before the EQ an anomalous increase of the gradient values began simultaneously with a decrease of the phase velocity values. In the papers [11], [12], [13], [14] the phase-gradient method is used to investigate the gradients and the phase velocities of the ULF geomagnetic emissions before the EQs of 2000 near the Izu peninsula. In these works it is suggested that an anomalous behavior of the gradient and phase velocity values before strong EQs should be connected with two processes in the region of a future EQ: first – formation of anomaly with increasing conductivity and second – appearance of the wide-band ULF electromagnetic emissions from the region of a future EQ hearth. According to [15] the anomaly of conductivity appears due to tectonic processes or (and) magma rising. Natural ULF electromagnetic waves propagating from the ionosphere to the ground are reflected at the lithosphere anomaly and we can observe increased ULF magnetic field at the Earth’s surface. One of the sources of the wide-band ULF electromagnetic emissions of the future EQ hearth is a process of microcracks formation due to tectonic processes. Increased magnetic field values lead to increase in gradients of the field directed to the future EQ epicenter. In this case the phase velocity vectors will point out of these sources. Decrease of the phase velocity values before the seismic active period can be explained as the increase of the conductivity in the region of the future EQ hearth.

4 Conclusion

Briefly we’ll summarize our experimental results.

1. The vectors of the gradients of the magnetic fields measured at ground are usually pointing to the source of the ULF EM waves. It is possible to locate and monitor the source of the ULF magnetic disturbances that can be implied as regions with the enhanced conductivity produced by the HF powerful radio transmitter in Tromso.
2. Anomaly behavior of gradient and phase velocity vectors of ULF (F<1 Hz) geomagnetic disturbances were investigated for two EQ events in Japan (M>6) in 2000 and (M=5.8) in 2003. It was found that the gradient and phase velocity values had anomaly changes 3-6 months before the strong EQs. New direction of the gradient vectors arose during this period – the directions to the forthcoming EQ epicenter. The directions pointed out of the forthcoming EQ hearth arose for the phase velocity vectors. We believe that the gradient and phase velocity vectors of the ULF geomagnetic disturbances are of great importance for a short-term prediction of strong EQs

ULF magnetic gradiometer is a general purpose tool that can be used in different regions of the Globe and can be applied as the solution of multiple magnetometric tasks. The main ones are - monitoring and detecting the sources of ULF electromagnetic emissions.

Aknowledgements

The work has been partly supported by INTAS grant #01-0614).

References:

[1] Kovtun A.A. Using of natural electromagnetic field of the Earth under studying of Earth's electroconductivity. St.-Petersburg, Leningrad University, 1980, 195 p.

[2] Kopytenko Yu.A., Raspopov O.M., Troitskaja V.A., Shlish R. Some results of analyzes of continues geomagnetic pulsations of Pc4 type. *Geomagnetism and Aeronomy*, V.12, N4, 1972, p. 720 - 726.

[3] Kopytenko Yu.A., Zaitsev D.B., Kopytenko E.A., Voronov P.M., Amosov L.G, Timoshenkov Yu.P. «Magneto-Variation Complex MVC-1DG». Proceedings of the Ist International Conference on Marine Electromagnetics «Marelec-97», 23-25 June 1997, p.10, London, UK.

[4] Kopytenko Yu.A., Ismaguilov V.S., Kopytenko E.A., Voronov P.M., Zaitsev D.B. Magnetic location of sources of geomagnetic disturbances (in russian). DAN, "Geophysics", V. 371, № 5, P. 685-687, 2000.

[5] Pudovkin M.I., Raspopov O.M., Klejmenova H.G. Disturbances of electromagnetic field of the Earth. Part 2. Leningrad, Russia, Leningrad University, 1976, 271 p.

[6] Kopytenko Yu.A., Voronov P.M., Ismagilov V.S., Kopytenko E.A., Zaitsev D.B. Spatial - temporal characteristics of geomagnetic pulsations.// Proceedings of the 1st International Conference on Marine Electromagnetics "Marelec-97", 23-25 June 1997, p.P2, London, UK.

[7] Kopytenko Yu.A., Voronov P.M., Ismagilov V.S., Kopytenko E.A., Zaitsev D.B., Molchanov O.A., Hayakawa M., Hattory K. Magnetic disturbances in ULF range connected with seismic sources.// Proceedings of the 2nd International Conference on Marine Electromagnetics "Marelec-99", 5-7 July 1999, Brest, France, pp.435-445.

[8] Kopytenko Yu.A., Ismagilov V.S., Kopytenko E.A., Rietveld M., J. Kangas. Investigation of ULF magnetic disturbances during the heating campaign in March 2004. Effects of Artificial Action on the Earth Ionosphere by Powerful Radio Waves. 4th International Suzdal URSI Symposium ISS-04. Book of abstract. Moscow, October 19-21, 2004, p.64.

[9] Shibkov S.A., Pudovkin M.I., Kotikov A.L. Small-scale field-aligned currents and plasma motion in auroral arcs. Geomagnetism and aeronomy, 2005, v.45, N4, p.p. 1-7. (in Russian).

[10] INTAS 97-1162, Project "BEAR", Final report

[11] Kopytenko Y., Ismagilov V., Hayakawa M., Smirnova N., Troyan V., Peterson T. Investigation of the ULF electromagnetic phenomena related to earthquakes: contemporary achievements and the perspectives. Annali di Geofisika, V. 44, № 2, P. 325-334, 2001.

[12] Kopytenko Yu.A., Ismaguilov V.S., Hattori K., Voronov P.M., Hayakawa M., Molchanov O.A., Kopytenko E.A., Zaitsev D.B. Monitoring of the ULF electromagnetic disturbances at the station network before EQ in seismic zones of Izu and Chiba peninsulas. In: "Seismo Electromagnetics: Litosphere-Atmosphere-Ionosphere Coupling". Eds. M.Hayakawa and O.A.Molchanov. Tokyo: TERRAPUB. P. 11-18. 2002.

[13] Ismaguilov V.S., Kopytenko Yu.A., Hattori K., Voronov P.M., Molchanov O.A., Hayakawa M. ULF Magnetic Emissions Connected with Under Sea Bottom Earthquakes. Natural Hazards and Earth Sys. Sci., V. 1, P. 1-9, 2001.

[14] Ismaguilov V.S., Kopytenko Yu.A., Hattori K., Hayakawa M. Variations of phase velocity and gradient values of ULF geomagnetic disturbances connected with the Izu strong earthquakes. Natural Hazards and Earth Sys. Sci., V.20, P.1-5, 2002.

[15] Uyeda S., Hayakawa M., Nagao T., Molchanov O., Hattori K., Orihara Y., Gotoh K., Akinaga Y., Tanaka H. Electric and magnetic phenomena observed before the volcano-seismic activity in 2000 in the Izu Island Region, Japan. Proc. of US Nat. Acad. of Sci., V. 99, №.11, P. 7352-7355, 2002