Изв.Крымской Астрофиз.Обс. 99, 143–151 (2003)

ИЗВЕСТИЯ
КРЫМСКОЙ
АСТРОФИЗИЧЕСКОЙ
ОБСЕРВАТОРИИ

УДК 550.380

On the practicability of VLF ionosphere sounding in the seismo-active regions on the basis of RNS

V. Fidelis

Crimean Astrophysical Observatory, 98409, Ukraine, Crimea, Nauchniy

Поступила в редакцию 3 июля 2003 г.

Аннотация. О РЕАЛЬНОСТИ СДВ-МОНИТОРИНГА ИОНОСФЕРЫ В СЕЙСНОАКТИВНЫХ РЕГИОНАХ НА ОСНОВЕ РАДИОНАВИГАЦИОННЫХ СИСТЕМ. Анализируются методологические особенности изучения литосферно-ионосферных связей в сейсмоактивных регионах посредством мониторинга ионосферы на сверхдлинных волнах (СДВ) на базе существующих радионавигационных систем. Систематизирован радиоволновой метод зондирования ионосферы и внесены предложения в его методологию. Рассмотрены особенности СДВ-мониторинга в зоне разломов и его сочетание с магнитотеллурическим зондированием. Предложено осуществить СДВ-мониторинг сейсмической активности Северо-западной части Кавказа и Южного Крыма на фиксированных частоте и трассе.

ON THE PRACTICABILITY OF VLF IONOSPHERE SOUNDING IN THE SEISMO-ACTIVE REGIONS ON THE BASIS OF RNS, *by V. Fidelis.* The methodological peculiarities of lithosphere-ionosphere coupling study in seismoactive regions by means of VLF (Very Low Frequency) ionosphere sounding on the basis of existing radionavigation systems (RNS) are analyzed. The radio-wave method has been systemized and the suggestions to its methodology are maid. The peculiarities of VLF monitoring in the fault zones and its combination with magnetotelluric sounding are considered. It is suggested to carry out VLF monitoring of seismic activity of North-West Caucasus and South Crimea on settled frequency and route.

Keywords: VLF, ionosphere – sounding, earthquakes – precursors – prognosis

1 Introduction

The long statistical study in the last years has proven some abnormal VLF signal variations related to seismic activity. This stipulates the study of ionosphere-lithosphere coupling processes in seismoactive regions by means of VLF ionosphere tracking on the basis of existing radionavigation systems (RNS). Amongst a few seismoionospheric precursors this new one is seems to be very practicable in seismoactive regions which lying close to circle connecting RNS transmitter and VLF receiver.

The VLF earthquake (EQ) prognosis may be developed in two main directions:

- observation of changes in homogeneous ionosphere structure;
- registration of appearance of localized ionospheric irregularities during the earthquake preparing stage.

These two directions may be taken as basis for searching for short – time VLF subionospheric prognostics in areas which likely to be struck by major tremors. VLF precursors inevitably are associated with Earth-ionosphere waveguide (EIW) property and, mainly, with reflecting heights in this frequency band. Experimental diagnosis of VLF precursors as a rule concluded in detecting of amplitude and phase of received VLF signal and their quanlitative analysis.

It is desired to quantify the earthquake signature by means of broadening of detecting VLF signal parameters and therefore to improve the experimental prognosis of future earthquakes.

The methodology of VLF signal reception may differ for short and long distances. In first case the determining propagating factor may be ground wave, in the second one many times repeated radiowave repulsing from interface boundary may cause the multimode propagation and interference. Recent seismic events have demonstrated that faults exert seismic effects beyond the usual. They may store a large amount of potential energy, which may be realized in rupturing events. Two-dimensional structure of fault conductivity and conflicts on boundaries of moving blocks may generate low-frequency emissions which phenomena may be found in ionosphere by VLF signal tracking.

Seismoionospheric precursors bear information about the lithosphere changes preceding an earthquake and are displaying, in main, as ionosphere reflecting heights variations, their critical frequency deviations and electron density changes.

Measurements of the ionosphere disturbances are routinely taken by satellites and analyzed for earthquake precursors. Survey of anomalous effects in the real helio-geophysical environment is a difficult tusk and its statistical analysis has many particularities.

Satellite data interpretations were summarized in (Larkina, 1998) as wave's field intensity changes in frequency range from parts of Hz to tens of kHz before a few hours of earthquake, a powerful particles arising, plasma's density and temperature changes before a main shock.

The registered electromagnetic effects have recently acquired some theoretical basis. In quiet geomagnetic periods in the ionosphere some relative equilibrium between energetic electrons and low-frequency emissions has become settled.

A nonlinear coupling with Alfven waves, generated by seismoelectric transformation in the earthquake's preparing zone exited low-frequency emissions in the upper ionosphere and the magnetosphere.

Forthcoming earthquakes cause irregularities not only in the regular ionospheric structure, but also in its irregular features (*E*– and *F*– spreading, *Es* appearance, anomalous traces like stratification, etc.) (Ruzhin and Depueva, 1996).

A thorough quantitative estimation of penetration characteristics from an underground seismic source into the atmosphere, ionosphere and magnetosphere was represented in (Molchanov et al., 1995).

Because of dissipation in the medium the calculations were made in the ULF range. It was shown that intensities of electromagnetic fields on the ground surface and in the ionosphere are drastically depend on the configuration of source, its type, polarization, dimension and depth. Only *TE* wave induced by the azimuthal magnetic type source can really penetrate into the ionosphere, the penetration of *TM* mode radiation is confined in the Earth - ionosphere waveguide.

The transmitted ULF energy into space plasma converted into obliquely propagated dissipated magnetosoundic and Alfven modes, the first is spreading in the upper ionosphere and the second can propagate into the magnetosphere. As a result of nonlinear Alfven wave conversion in the ionosphere may arise VLF seismogenic emissions.

In Tian and Hata, (1996) were analyzed on the inland and trench earthquake types the effects of ELF radiation from a randomly distributed discharging dipole sources near the Earth's surface. The estimated magnetic field's strength is corresponded to observed one in Ito city of the 1995 swarm.

Due to evolution of seismo-geophysical events in the lithosphere, earth's crust and on the earth's surface in the ionosphere arise disturbances which may effect the radiowaves propagation conditions and change the phase and amplitude of navigational signals propagating inside the Earth-ionosphere waveguide.

The particularities of VLF radiowave propagation along the traces crossing the seismoactive regions were discussed in Gufeld et al., (1992), Reutov and Marenko (1995).

In Haykawa et al., (1996) was used VLF signal method by which were measured the propagation characteristics. They found abnormal behavior (especially of phase) a few days before the main shock of the 1995 Hyogo-ken Nanby earthquake. By computer simulation was suggested that observed effect can be explained by decreasing in the VLF reflection height. This decreasing was related to either increase in the reference atmosphere conductivity or an increase in the density of charged particles.

So that the theoretical and numerical analysis of seismoelectromagnetic (SEM) emissions demonstrates the relevance of the study of the ionosphere property variations and the possibility of gaining an insight into the nature of SEM precursors using ground-based measurement techniques.

The VLF monitoring of geophysical media above the extended regions is far accessible for registration from ground based RNS and is of great interest in comparison with satellite one because of its integral character.

The purpose of the present paper is to systematize the principles of radiowave method, the variety of observable parameters and suggestions for extension the number of precursor types and thereby to improvement of VLF radiowave methodology.

2 Ground wave propagation mechanism

The study of ground wave propagation mechanism may give the picture of the surface impedance changes related to seismic activity, which are connected with electrical resistivity changes. Registration of Earth's crust electrical resistivity changes have been successfully used for earthquake prediction in periods of hours and weeks prior to event (Peddel and Freeman, 1997). The local resistivity change can be associated with strain in the medium, the large changes relate to observation in the earthquake focal region.

The surface measurements of electrical resistivity are made using artificial electric current sources or highly sensitive variometers.

The polarized characteristics of VLF ground wave are conditioned by appearance of inhomogeneous conductivity on the Earh's surface before an earthquake due to stress increasing in homogeneous media. The mechanisms generally invoked in electromagnetic emissions are: direct wave generation by rocks compression near the focal point and the cracking of surface crustal layers in the earthquake's preparing zone, redistribution of electric charges, piezoelectric effect and others.

Earth's inhomogeneous conductivity may effect both subionospheric and ground wave propagation (Soloviev, 1997). Daily variations of telluric field before an earthquake supposedly caused by periodic changes of resistance of mountain rocks during the earthquake's preparing stage in the dilatable zone were found by Meyer and Teisseyer (1989). During observation of magnetic and telluric fields variations on the profile, directed perpendicular to Big Caucasus Mountains axis were registered uncorrelated with magnetic field short-periodic variations of telluric field, quantitatively pro rata the number of registered earthquakes (Trofimov, 1994).

Separation of seismoelectric events in the telluric variations performed visually on absence at moment of their appearance the analogous variations in magnetic fields that eliminate their association with field of ionospheric origin.

The concept of surface impedance is commonly used in studies dealing with ground wave propagation. For characterizing Earth's surface electrical inhomogeneities the relative impedance function of spatial variables may be introduced as:

$$\Delta(x,y,z,t) = Z'/Z_o = \Delta_1 \cdot Q(x,y,z,t),$$

where surface impedance $Z' = E_x/H_y$ at z=0, $Z_o = 120\pi\Omega$, Δ_1 – relative surface impedance for upper layer, Q – the function of electrical parameters. Note that Z' is a complex parameter.

The polarized characteristics of ground wave are conditioned by this surface impedance which changes before the earthquake due to increasing of atmosphere conductivity and ionosphere modes are depending on frequency properties of EIW.

In the trench type crust, particularly in the peninsula and island sites, the appearance of electric currents before the earthquake may be complicated by shore effect and sea water shunting. In the air the vertical electric field E_{1z} invariably greater than horizontal one, E_{1x}, as much as $[\epsilon^2 + (60\lambda\sigma)^2]^{1/4}$ times, where ϵ is dielectric permittivity, σ – electric conductivity, and λ – wavelength.

For $\lambda = 30$ km, $\sigma = 4S \cdot m^{-1}$, $\epsilon = 20$; $E_{1z} = 2700E_{1x}$ in the air and $E_{2x} = 2700E_{2z}$ in the sea (Fidelis, 1999a). So that the VLF signals in air, as rule, are receiving on vertical antenna and in the sea – on horizontal one. In the coil antenna, which detects magnetic component in the air and sea induced signals have the same amplitude.

The simultaneous detecting of electric field components E_{2x}, on sea shelf and E_{1z} in boreholes on seashore may improve signal/noise ratio thanks to ocean filtering and give information related to preparing phenomena of trench type earthquakes.

3 The multimode ionospheric propagation

Due the electrical field changes in the earth's crust the electromagnetic energy penetrates in the nearby space and cause the rise and decline of ionospheric layers heights. This process accompanied by decreasing of electron density in its maximum (Larkina, 1998). Also there are effects of formation of sporadic layers in the ionosphere on space scale of hundreds of kilometers, intensification of ionospheric plasma vorticity interpreted as result of parametric fluctuation excitation between the upper hybrid resonance and critical layers and emergence of ionospheric inhomogeneities with space scale up to thousand kilometers.

The VLF signals propagating in the waveguide Earth – ionosphere are reflecting from the ionosphere and in the reception place have the interfering character and are consisting of ground wave and a number of reflected from ionosphere modes. In the case of localized or extended ionospheric irregularities their effects may be characterized in the perturbation of ionosphere modes and dominant ground wave within an inhomogeneous area.

The parameters of ionosphere modes are depending from frequency properties of EIW.

The ionospheric layers with low density have high sensitivity to *EM* field distortion. For example, the midlatitude ionospheric *E*-layers are characterized by high concentration of metallic ion layers and are distinguished by the high correlation of Hall and Pedersen conductivities. Moreover, the sporadic *E*-layers may have the electron densities, as much as two orders higher than background (Woodman et al., 1991). The electric inhomogeneities in the sporadic *E*-layers have sufficiently long time of existence (the first tens of minutes) because the boundary layers with zero conductivity prevent the shorting of electric currents which appear in the ionized plasma. The polarization processes in the sporadic *E*-layers may occur and in the periods of quiet geomagnetic conditions.

The gravitational waves in the ionosphere model may play the role as inhomogeneity generator in the *E*-layer in the form of metallic ions spots (Tsumodo et al., 1994).

The VLF signals, propagating in the waveguide Earth – ionosphere are reflecting from the ionosphere and in the reception place have the interfering character and consist of ground wave and a number of reflected from ionosphere modes. In the case of localized or extended ionosphere irregularities their effects may be characterized in the perturbation of ionospheric modes and dominant ground wave within an inhomogeneous area.

The phase variations of interfering signals directly connected with the changes of ionosphere reflecting layers heights. Observed on fixed distance VLF signal parameters mainly depends on the *D*-layer electron density profile (Haykawa et al., 1996).

In average, in the VLF band under the fluctuations in the ionosphere the field's variations are order of 10 – 30 %, the variation time varies from tens minutes to hours. These parameters may be detectable above the background.

In the Omega receiver is derived the radionavigation parameter – the additional phase of VLF signal defined as (Kinkulyikin et al., 1979):

$$\varphi = -argV,$$

where V is the complex co-ordinate function, named as the attenuation factor.

Under VLF propagation above the high mountain range there emerge the second and higher propagating modes. So that the additional phases of first and next modes may be used as ionosphere informative parameters.

Under the multimode propagation the variation of additional phase has the interfering character, which describes the electric properties of ionosphere.

For signal, consisting from two spectral components, the change of additional phase of first mode, caused by the interference with second one may be defined as:

$$\Delta\varphi_{add} = argtg[\gamma \sin\varphi/(1 + \gamma\cos\varphi)],$$

where $\gamma = |E_z^{(2)}|/|E_z^{(1)}|$ – amplitude relation of two signal modes, $\varphi = argE_z^{(2)} - argE_z^{(1)}$ – phase difference of first and second modes in the reception place.

There are the great number of natural factors interfering on the VLF signal, propagating in the spherical EIW (Arsenin, 1976; Remenets, 1972). But upon constant base the subject of analysis is comparatively rare variation of additional phase, conditioned by the sudden ionosphere distortions. The ionosphere distortions are filtered from magnetotelluric ones and exposed to statistics those ones which correlated with the anomalous changes of natural *EM* field in the earthquake's preparing period.

Because of sudden ionosphere perturbations arise an additional errors, which may estimated as (Burges and Walker, 1970):

$$\Delta = M(t/\tau_s)exp[-(1 - \tau_s)^2/2],$$

where M and τ_s are parameters which characterize changes of additional phase owing to sudden ionosphere disturbances.

4 Combination of VLF tracking with other instrumental methods

The monitoring of anomalous Earth's *EM* field variations by active VLF signal tracking may be combined with detecting of passive EQ precursors and traditional seismosurvey methods.

Compilated both ground passive *EM* and active VLF ionospheric data, along with seismic survey are subjected to statistics (Fidelis, 1998). The ionosphere survey may give the total picture of regional seismoactivity and registration of anomalous variations of SEM field in high-frequency band on the seismic stations by means of broad-band loop antennae may give the azimuth of the earthquake's preparing zone (Vallanatos, Novikos, 1997).

The principle of earthquake prediction on the basis of VLF survey in combination with detecting of natural Earth's *EM* fields, the daily periodic variations of telluric field measurements, and traditional instrumental seismoservey is shown on Fig. 1.

The VLF signal method may be combined with observation of subsurface electromagnetic fields in ULF band (Matsumoto et al., 1996). The study of temporal variations of seismic swarm activity and duration of anomalous subsurface field preceded the earthquake may give clue for long-time prognosis.

5 Prognosis of seismic activity in fault regions

The high seismic hazard in fault areas is confirmed by several large strike-stripe events in past decades when some sites have been endured by several devastating earthquakes.

28 December 1994 Sanriku-Oki M=7.7 earthquake was followed by two major subevents with whole rupture time about 55 s with estimated fault area of the main rupture $4000km^2$ (Sato et al., 1996). The focal mechanism solutions suggest low-angle thrust faulting along plate boundary between the Pasific and North American plates. A similar interplate event occurred in this site 26 years earlier, that is surprising because the current recurrence time interval of large earthquakes is thought to be about 100 years.

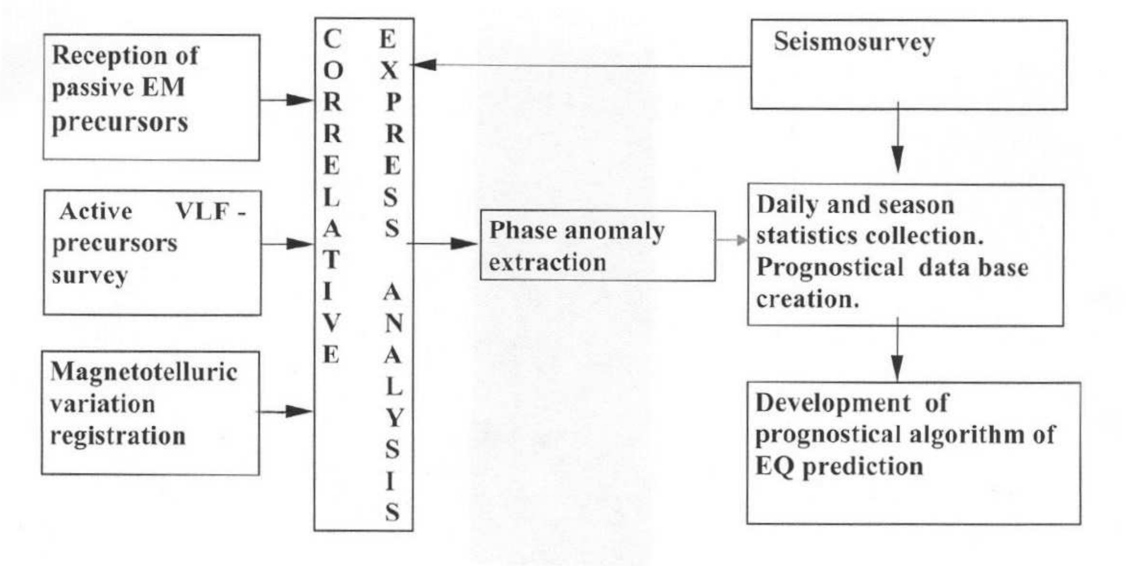

Fig. 1. The principle of earthquake prediction method development by electromagnetic precursors

A destructive M=7.4 earthquake occurred 17 August 1999, 100 km east Istanbul, near the city Izmit, on the North Anatolian fault. The 1600 km fault's boundary slips at an average rate 2 – 3 cm yr^{-1} and only in past century it has ruptured in a sequence of eight M>7 events (Hubert-Ferrary et al., 2000).

And there there are no evidences that in the following decades the rupturing events in this site have not been recurrent.

In 1994, M=6.7 Northridge earthquake, which was the continue of California succession, ruptured previously unrecognized 'blind' thrust fault beneath Los Angeles suburb (Shaw, 1998).

A large active fault earthquake M=7.2 occurred near Kobe, Japan January 17, 1995 has damaged for 20 s 130 billion USD property and gone away the 6 thousands of peoples lives.

The faults can experience a Loucomb stress increase and therefore the loading slips (Nalbant et al., 1998). Experienced by loading stresses faults may hosted many historical earthquakes.

Stress accumulates on the fault continuously as a result of plate motion. When the whole fault system is near failure, a critical stage is reached that is characterized by an extreme susceptibility to small perturbations and strong correlation between different parts of the system. Small stress increases (1 – 5 bar) are then sufficient to trigger failure in the upper crust, and the fault tends to rupture over most of its length in a cascading sequence of earthquakes (Hubert-Ferrary et al., 2000).

Induced on faults stresses may deform crust with such rates that arising earthquakes may have magnitude as much as two times higher then earthquake in such environment without fault.

All existing diversification of tectonic faults may be reduced to strike-slip vertical fractures moving laterally with respect to one another and inclined thrust with reverse fractures where the block above the fault move up with respect to the underlying blocks. The high lateral stresses in their interacting boundaries, which have definite viscosity and elasticity, create a great stock of elastic potential energy, partly released in the earthquake, and tectonic movements, relucting against these stresses, maintain this background energy stock (Dobrovolsky, 1992).

In the stressed regions occur the physico-chemical processes, which change the mean properties of definite volume of rocks and accompanied by appearance of inhomogeneities, which dimensions define the energy of future earthquake. These inhomogeneities are bringing about the disturbances in the geophysical fields, perceived as precursors.

Under modest slip rates (mm/year) and increased stress (1 – 2 bar), fault accumulates the large seismic moments about 10^{20} N·m, which may be realized in the ruptures and dislocations of earth's crust

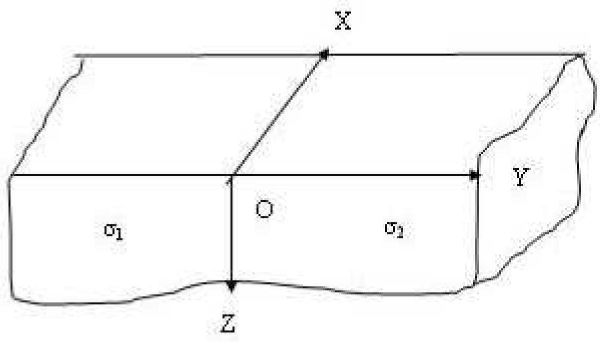

Fig. 2. The simple bilateral fault conductivity structure

about few meters (Sato et al., 1996).

The fault may be approximated by bilateral conductivity structure as shown on Fig.2, where σ is electrical conductivity ($\Omega^{-1}m^{-1}$). X, Y, Z – coordinates were chosen with Z vertically up from earth's surface.

This 2-D conductivity structure conditioned by arising on fault E– and H-polarization (TM– and TE-waves), having different properties, defined by electric current continuity on fault's boundary. Under E-polarization the electric field is headed along fault boundary (OX axis) so that currents with $j_x = \sigma \cdot E_x$ density flow in the same direction. Owing to abrupt surface conductivity structure under E continuity arising j_x break-off conditioned by appearance of non-zero H_z component. H-polarized field (the currents flow in fault's transverse direction) does not generate H_z component due to model and field symmetry. These differences among E and H-polarization are used for estimation of fault structure direction.

The components of impedance tensor on fault are different too. Thus $Z_{xy} = E_x/H_y$ (E – polarization) continued on fault, and $Z_{yx} = E_y/H_x$ (H-polarization) discontinued. In observing points over deep fault $Z_{xy}(0)$ and $Z_{yx}(0)$ are different (Larsen, 1973). Corresponding two types of magnetotelluric sounding (MTS) curves $\rho_{xy} = (1/\omega\mu_o) \cdot |Z_{xy}|^2$ and $\rho_{yx} = (1/\omega\mu_o) \cdot |Z_{yx}|^2$ ($\mu_o = 4\pi 10^{-7}$ is magnetic permeability and ω is circular frequency) are used in MTS technique for estimation of geoelectric fault structure. 2-D fault distorts MTS curves relatively uniform 1-D half-space. But it is necessary to take into account complication of geoelectric picture in trench type faults due to coastline effects associated with concentration of electric currents along the conductivity contrast (Larsen, 1973).

Theoretical treatments usually have ignored lateral EIW properties change along VLF path. Analysis has always been restricted to the profile of ionosphere height along VLF trace.

Above mentioned 2-D fault conductivity structure may change lower boundary of EIW and so modify it in whole.

A simple model is then to assume the EIW everywhere uniform except at fault interface with a $\Delta\sigma$ step. The question is whether a small change in conductivity associated with fault's boundary can significantly alter EIW relatively uniform conductivity. But another effect may be of great importance.

In situations where the various physico-mechanical processes in fault regions affect changes in the horizontal structure of rock properties the emitted low-frequency electromagnetic fields may disturb the EIW.

It is shown (Wait, 1964) that ionosphere depressions, transverse to great circle part connecting VLF transmitter and receiver, lying within the first Fresnel zone, can modify the phase of the received signal.

So that it is of great interest to study the faulted regions by VLF tracks which crosses faults in transverse directions.

The magnetotelluric measurements of MTS curves distortion in active regions along with VLF signal method may improve earthquake prognosis in a fault environment.

6 Development of seismoprognostic Crimean testing area

Crimean region has a complicated geological structure. Its high tectonic mobility, the presence of large active fault are the reasons of abnormally high seismic activity in some its areas. The sharp differentiation of geological and geophysical parameters in the faulted structure may bring about the appearance of electromagnetic effects prior to seismic events which may cause the ionosphere parameters variation.

The main feature of Crimean peninsula is large active Georgian fault. It separates rock -folded thrusting of mountain Crimea from structure of plane Crimea. Development of seismoprognostic testing area on this fault is of no small importance for estimation of seismicity of whole Crimea.

It is supposed to develop VLF monitoring at fixed frequency and reception distance on the VLF Omega path Krasnodar - Sevastopol (Fidelis, 1999b). On this rather short-distance may be studied earthquake signature from epicentra localized in the North-West Caucasus and South Crimea.

So that the supposed VLF path resembles the Tsushima-Inube one in Japan.

But our middle latitudes are characterized by stable local VLF propagation conditions on the reflection height, the high regularity of nocturnal and diurnal phase variations and the minimum of geomagnetic disturbances, so they are more sensitive to specific ionosphere distortions.

The bottom boundary of waveguide Earth – ionosphere is stabilized by high conductivity of Black sea waters and principal factors of EM anomalies in ionosphere may be registered by different instruments.

The favourability of this method for these regions is concluded in the following circumstances:

a) the VLF Omega signal path situated in the middle latitudes, where the geophysical effects in the ionosphere are not strongly expressed in comparison with auroral zone and low latitudes, and horizontal plasma conductivities in ionospheric layers are comparable by the value with the vertical ones in the equatorial regions and may create polarization fields with high relation of order to background, formed due the dynamo-effect. These polarization fields are sufficient for creation of instabilities, high-sensitive to lithosphere-ionosphere coupling and to distortions in the Earth's subsurface layers;

b) the mountain inhomogeneities may be important factor of swinging out of gravitational waves in the earthquake's preparing zones and intensification of the ionosphere vortexity on the 80-120 km level in the result of geophysical fields perturbation transmission from earth's crust to ionosphere.

For VLF signals the first Fresnel zone on a flat earth connecting points at separation distance d has maximum width $S = (\lambda d)^{1/2}$ (Wait, 1964).

For VLF path Krasnodar – Sevastopol ($\lambda = 30km$, $d = 425km$) it is seem that S= 112 km. So that the limit of VLF signal sensitivity on this path will be $S/2 = 56km$.

7 Conclusion

Conventional geophysical survey fail to recognize some structural variations in the Earths' layers properties which may be reliable earthquake's prognostics.

The observation of the EM effects-earthquake precursors may give greater sensibility in the comparison to registration of inner gravitation waves, emerging in the earthquake's preparing period and reflecting from the upper mantle layers.

The VLF signal method has no limits for surveying of seismogenic regions. The advantages of regular tracking of some active regions and the possibility to resolve the VLF survey problem only for a little part of space segment cost are prevailing factors for choosing of this method.

As a result of statistical study may be found the spatio – temporal distribution of electromagnetic prognostics from an earthquake epicentra close to VLF radiowave traces.

The absence of worldwide data on VLF prognostics exclude the possibility of retrospective analysis of earthquake events and associated electromagnetic phenomena. So that development a new RNS paths counting on continuous work along with complicity of seismic data and methods may contribute to the development of earthquake prediction methodology.

References

Arsenin V. J. et al. // About influence of geomagnetic field on the propagation of VLF and LF waves in the nearest zone of Earth-ionosphere waveguide. M. 1976. P. 19. (in Russian).

Burges B. and Walker D. // J. Inst. Navig. 1970. V. 23. N. 1. P. 49.

Dobrovolsky I. P. // Fizika Zemli. 1992. N. 6. P. 31. (in Russian).

Fidelis V.V. // Reports of the Ukrainian Academy of Sciences. 1998. N. 1. P. 163. (in Russian).

Fidelis V.V. // Advances of Modern Radioelectronics. Foreign Radioelectronics. 1999a. N. 8. P. 59. (in Russian).

Fidelis V.V. // Proceedings of the International Symposium on Fundamental and Applied problems of monitoring and prognosis of natural disasters (Sevastopol, September 1998). Part II. P. 74. Kiev. 1999b. (in Russian).

Gufeld I.L., Rozhnoy A.A. , Tyumentsev S.N., et al. // Izvestiya AN SSSR. Fizika Zemli. 1992. P. 103. (in Russian).

Hayakawa M., Molchanov O., Ondoh T. and Kawai E. // Journal of Atmospheric Electricity. 1996. V. 16. N. 3. P. 247.

Hubert-Ferrary A. et al. // Nature. 2000. V. 404. P. 269.

Kinkulyikin I. E., Rubtsov V. D. and Fabric M. A. // The phase method of co-ordinate definition. M. Sovetskoe radio. 1979. P. 279. (in Russian).

Larkina V.I. // Advances of modern radioelectronics Foreign Radioelectronics. 1998. N. 5. P. 15. (in Russian).

Larsen J.C. // Physics of the Earth and Planetary Interiors. 1973. N. 7. P. 389.

Matsumo T., Fujinawa Y. and Takahashi K. // Journal of Atmospheric Electricity. 1996. V. 16. N. 3. P. 175.

Meyer K., and Teisseyer R. // Phys. of the Earth and Planet. Int. 1989. V. 57. P. 45.

Molchanov O., Hayakawa M., and Rafalsky V. // J. Geophys. Res. 1995. V. 100. N. A2. P. 1691.

Nalbant S.S., Hubert A. and King G.C.P. // J. Geophys. Res. 1998. V. 103. P. 22469.

Orange S. // Proceedings of the IEEE. 1989. V. 77. N. 2. P. 287.

Peddel J.B., and Freeman E.M. // Proceedings of International Conference on Marine Electromagnetics. June 1997. London.

Remenets G.F. // Disertation thesis on the awarding of scientific degree of candidate of physico-mathematical sciences. Leningrad. 1972. P. 13. (in Russian).

Reutov A.P., and Marenko V. F. // Concept of radio wave forecasting system and experimental results. Moscow. IIA. 1995. P. 46. (in Russian).

Ruzhin Yu., and Depueva A. // Journal of Atmospheric Electricity. 1996. V. 16. N. 3. P. 271.

Sato T., Imanishi K., and Kosuga M. // Geoph. Res. Lett. 1996. V. 23. N. 1. P. 33.

Shaw J. // Cracking Los Angeles. – Nature. 1998. V. 394. P. 320.

Soloviev O.A. // Proceedings of International Conference on Marine Electromagnetics, June 1997, London.

Tian X. and Hata M. // Journal of Atmosperic Electricity. 1996. V. 16. N. 3. P. 227.

Trofimov I. L. // Fizika Zemli. 1994. N. 7 – 8. P. 91. (in Russian).

Tsumodo R.T., Fukao S., and Yamanoto M. // Radio Science. 1994. V. 29. P. 349.

Vallianatos F. and Novikos K. // Proceedings of International Conference on Marine Electromagnetics. June 1997. London.

Wait J.R. // Geophys J. Res. 1964. V. 69. N. 3. P. 441.

Woodman R.F., Yamamoto M., and Fukao S. // Geophys. Res. Lett. 1991. V. 18. P. 1197.