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The study of local sources of ULF geoelectric signals with steep fronts

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Abstract

The method for recognition and monitoring of ULF electrotelluric signals with steep fronts is presented. The method is based on the multicomponent measurements of the geoelectric field and recognition of the clusters of signals using the data of spatial-polarization filtering. This detects the local sources of the signals associated with the variation of mode of deformation of the medium. The method was applied to the study of geoelectric sources associated with aftershocks of the Racha-Djava earthquake. The field observations show with a fair degree of confidence that these signals are generated by a small number of local zones in the vicinity of the observer (at a range of tens-hundreds meters). The spatial distribution and the dynamic properties of the local sources are described. The analysis of observations leads to the conclusion that the dynamics of the local sources of ULF signals with steep fronts may be considered possible electrotelluric precursors of the earthquakes. Consideration is given to the feasibility of the well-known VAN method for earthquake prediction. The overall methodological aspects of the current studies of the electrotelluric precursors of the earthquakes are discussed.

Key words *geoelectricity – earthquakes prediction – method VAN*

1. Introduction

The study of Ultra Low Frequency (ULF) geoelectric signals with steep fronts is popular at the moment. Recently the author presented the new examples illustrating widespread occurrence of such signals in seismoactive zones (Chirkov, 2000, 2002). It is supposed that these signals may be associated with the specific evolution of mode of deformation of rocks before earthquakes.

The present work is devoted to an elaboration of the method for monitoring ULF electrotelluric signals with steep fronts. It is further development of an old idea (Sobolev and Morozov 1970; Ponomarev, 1987) concerning the search for electrotelluric precursors of earthquakes (see also Sobolev, 1992; Varotsos and Sarlis, 2002). The application of the electrotelluric method in geodynamic monitoring is attractive because it gives the possibility to provide a distant control of the medium state in real time using point measurements. In addition, it may be sensitive to detect a variation of the medium parameters in the wide range of time intervals – from a fraction of a second up to days and more.

In all, the method of monitoring based on the detection of geoelectric signals with steep fronts appears to be particularly importance, because these signals are easily recorded and recognized, and namely such signals are considered the possible precursors of earthquakes.

Signals with steep fronts were discovered on Kamchatka by Prof. G.A. Sobolev's group (Sobolev and Morozov, 1970). Signals have not

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been registered synchronously on several stations situated from each other at a distance of some tens of kilometers. On that basis the conclusion on their local origin has been made. As similar signals were not seen before the strong Ust-Kamchatka earthquake (1971, $M = 7$), interest in signals in Russia subsided.

Then Prof. P.A. Varotsos paid attention to these signals. Signals received the name SES (Seismo Electric Signals) and for about twenty years have been used by the VAN group for the prediction of earthquakes in Greece. As a result of these researches by the VAN group, some interesting phenomenological features of signals have been discovered and many successful predictions have been made (Varotsos and Alexopoulos, 1984a,b, 1987; Varotsos *et al.*, 1988, 1993, 1996; Varotsos and Lazaridou, 1991).

However, despite the large number of recorded signals and considerable experience of the practical prediction of the VAN group, the scientific community has not come to a consensus on the reliability of the prediction on the basis of electrotelluric precursors. This is a difficult problem mainly because the location and origin of sources of the electric precursors are not easy recognized. As a result, «the wind prevailing in the scientific community does not appear to be favourable for earthquake prediction research» (Uyeda, 2002).

Though works of the VAN group were subject to multilateral criticism most intensive during the years 1996-1998 (*e.g.*, Bernard, 1992; Geller, 1996a,b, 1997; Gruszow *et al.*, 1996; Kagan and Jackson, 1996; Bernard *et al.*, 1997; Geller *et al.*, 1997; Pham *et al.*, 1998, 1999, 2000; Pinettes *et al.*, 1998), the latest works (Uyeda, 2002; Varotsos and Sarlis, 2002) testify that the the question continues to remain open. The sides find newer and newer arguments in support of their points of view, but experimental results preclude a well-grounded conclusion on the correctness of one of the sides and despite perennial efforts, we have no essential advances in understanding the nature of electrotelluric precursors.

What is the reason for such a paradoxical situation? In our opinion the general cause of the paradox is mainly the local origin of precursory signals with steep fronts and unsuitability of existing techniques of measurements, data processing and prediction of earthquakes for such kind of signals.

In discussion devoted to the earthquake prediction of the VAN group, there are many unsettled problems which are concentrated around the same main three topics: the localization of the sources, the method of detection of the precursor signals against background noise taking into account the real inhomogeneity of media, and the overall scheme of the earthquake prediction. The following three separate sections of the article will be devoted to these three topics.

2. The local origin of the ULF signals and causal dependence of their sources on the change mode of deformation: experimental evidence

In our opinion, the principal cause of mistrust in the results of the VAN group is connected to the contradiction between the model of source SES in the epicenter of an impending earthquake which is proposed by the VAN group and their own results, which can be more easily explained on acceptance of a hypothesis about a local origin of source. There are a number of indirect indications testifying the inadequacy of the experimental data to the model of source SES in the epicentre.

This is the existence of sensitive zones and maps of selectivity, which is evidence of absence of simultaneous precursory signals on a network of the VAN group; absence of a large number of signals coincident with the time of the earthquake, when there are most dynamical processes in the epicenter; appearance of a signal not on all lines of a given station and so on.

There are also many reasons to think that the sources of observed electrotelluric signals are not arranged within the focal zone of the future earthquake, but are placed in the immediate vicinity of the observer. For example, (Gershenzon and Bambakidis, 2001) believe that the ULF signals have a local origin (see also Dobrovolsky *et al.*, 1989; Dobrovolsky, 1991; Gershenzon and Gokhberg, 1993; Gruszow *et al.*, 1996) and presented arguments in favor of the hypothesis of regional stress as a prime cause of the abnormal ULF signals observed before earthquakes. Ponomarev (1987) noted the remarkable similarity of empirical relation $\lg(\Delta U \cdot R) = (0.3 - 0.4) \cdot M + A_k$ established by Prof. Varotsos (between the amplitude of the signal ΔU, the magnitude M of the earthquake and the epicentral distance R) with other relation $\lg \cdot (\varepsilon^{1/3} \cdot R) = 0.43 \cdot M - 2.73$ (between the amplitude of the deformation ε, the magnitude M of the earthquake and the radius of the manifestation of deformation's precursor R) which was established by Dobrovolsky (1983) theoretically.

To test the hypothesis about the local origin of signals with steep fronts a special experiment was conducted during an aftershock sequence of Racha-Djava earthquake (29.04.1991, $M = 6.8$). Figure 1 shows the map of epicentral zones of the main shock and the strongest aftershock (15.06.1991, $M = 6.3$). It should be noted that the problem in hand demands a special measurement technique. Long lines are unsuitable for monitoring signals since the signal is registered only by one electrode of the line while the signal/noise relation is reduced due to the contribution of ionospheric disturbances, which is proportional to the length of a line. Furthermore, a change in potential on the common electrode can result in a false anomaly, which seems recorded by several lines. Using the amplitude of anomaly, normalized on length of the line, hides the false character of this anomaly. At best with such technique we receive a signal recorded on one or two lines, that it is not enough for an estimation of parameters of sources.

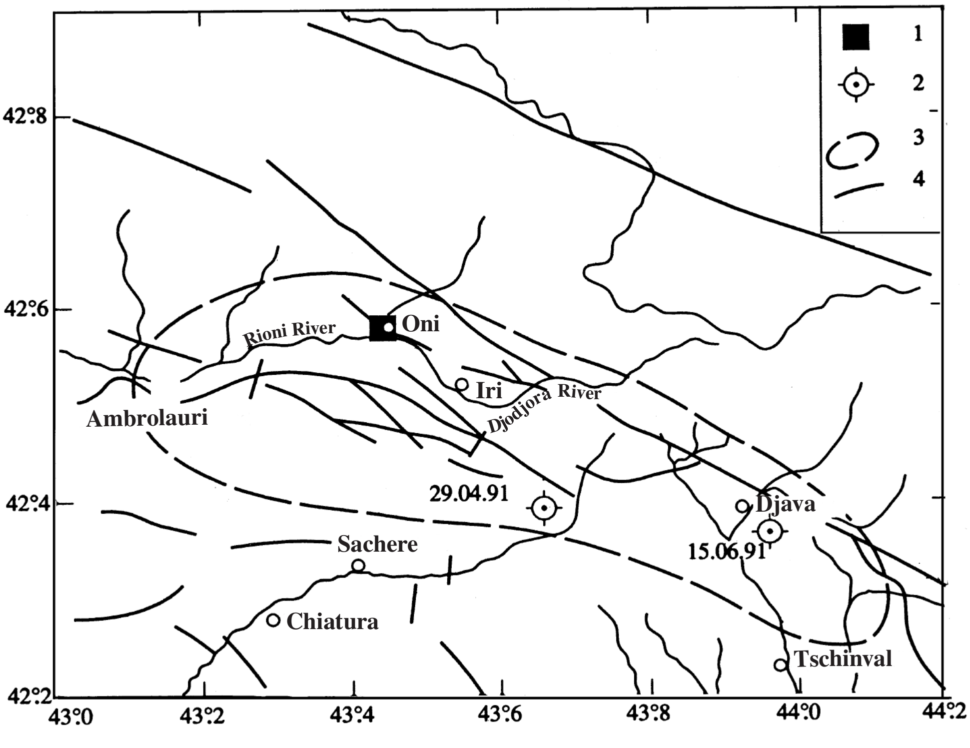

Fig. 1. The epicentral zones of the Racha-Djava earthquake (29.04.1991, $M = 6.8$) and the strongest aftershock (15.06.1991, $M = 6.3$). Here (1) is the point of observation, (2) indicates the epicenters, (3) is the pleistoseist zone, and (4) indicates the faults.

The basic idea is that two horizontal components of the electric field at two closely spaced points are recorded. In other words, the four independent lines are used to control the locality of sources. Figure 2 presents the disposition of measuring and generating lines. The distance between points is 70 or 200 m depending on the period of observation. From 23.05.1991 to 19.07.1991 the measurements were carried out at 1 and 2 points, and from 20.07.1991 to 20.08.1991 at 1 and 3 points. The daily measurements of the electrical resistance of the rock were made as well. Rock resistance was controlled using the same dipoles used for electrotelluric monitoring. Two additional orthogonal dipoles situated near measurements points were used as sources of a current (see fig. 2).

The measuring system consists of blocks of preamplifiers and a digital recording system. The former involves four identical preamplifiers with an amplification factor equal to 41. Analog filters were equivalent to the 0.033 Hz lowpass Butterworth filters. 12 bit ADC was used, the weight of LSB was 2.5 mkV, sample recording time was 30 or 60 s. High-quality «Travers» electrodes were kindly presented by Dr. M.M. Bogorodsky for this experiment. The special way of installation of electrodes in the ground was applied. Measurements were carried out at least every minute. Noise level allowed recording of ULF electric signals with steep fronts if their amplitudes were more than 20-30 mkV.

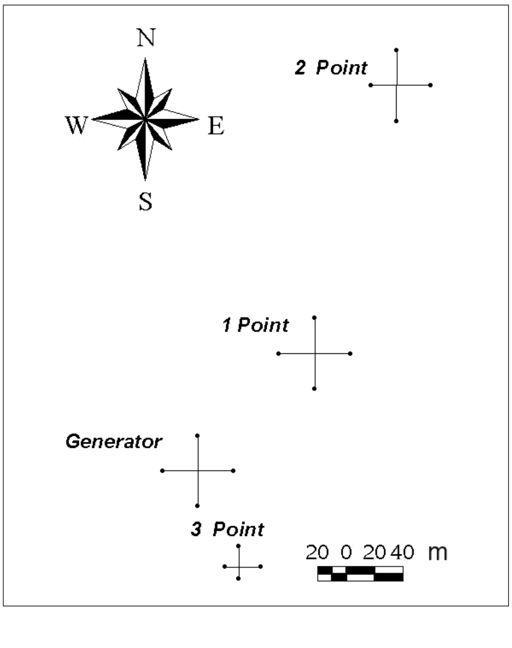

Fig. 2. The disposition of measuring and generating lines. The Arabic numbers designate the points of measurement.

The observations have shown an abundance of signals with steep fronts. We do not use the SES designation because we are not taking into account VAN «Rules» of SES detection. In our opinion, SES in the overwhelming majority of cases are a subset of signals selected on a technique offered by us. Many signals were recorded at two points with the ratio of amplitudes on measuring lines varying in a wide range. This fact itself may be easily attributed to the presence of at least several local sources. By manual processing some tens signals were detected with similar spatial characteristics. Some increase in the number of signals was revealed before the strongest aftershock of 15.06.1991.

Our opportunity for recording signals from the local sources depends on the intensity of sources, their position relative to the measuring system, and the registration threshold of the system. The lower the level of threshold is, the larger the area we can control. However, manual detection of signals of small amplitude is practically impossible. To solve this problem, a new algorithm for detecting synchronous signals with steep fronts has been developed. The idea consists in the analysis of spatial and polarization characteristics of the signals. The algorithm has two generic parameters. One of them is used for adaptation to the level of noise, and the other defines the level of requirements to quality of the analysis of spatial structure of sources. These two constants need to emerge once on the basis of the analysis of records by duration about one week and a further procedure of detection of signals is completely formalized. Several thousand signals were detected using this algorithm. Figure 3 gives an example where the significant number of detected signals of different amplitude with the same spatial structure is visible.

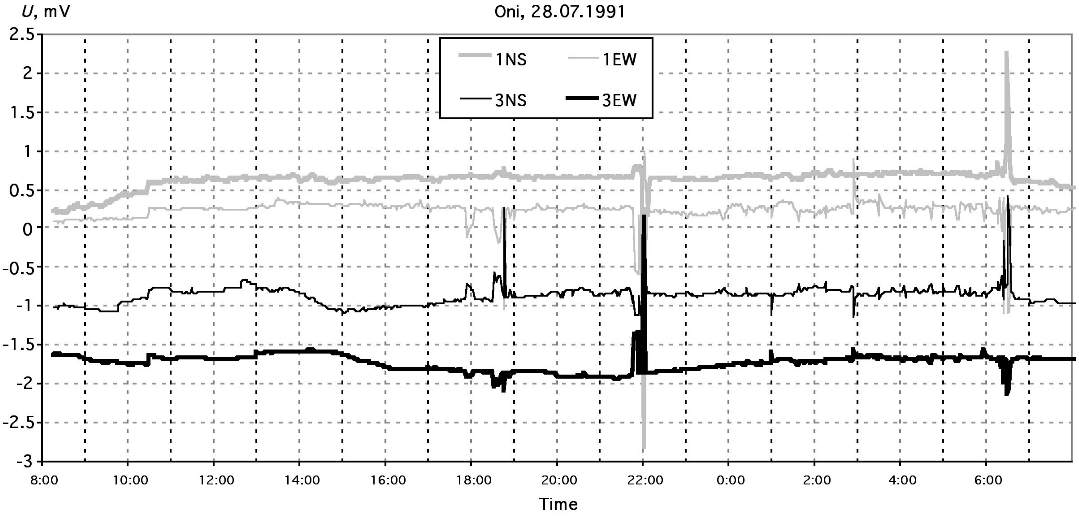

Fig. 3. Example of the records containing signals with steep fronts, which were registered at 1 and 3 points of measurement on 28.07.1991. The Arabic numbers designate the points of measurement. NS and EW specify directions of measuring lines.

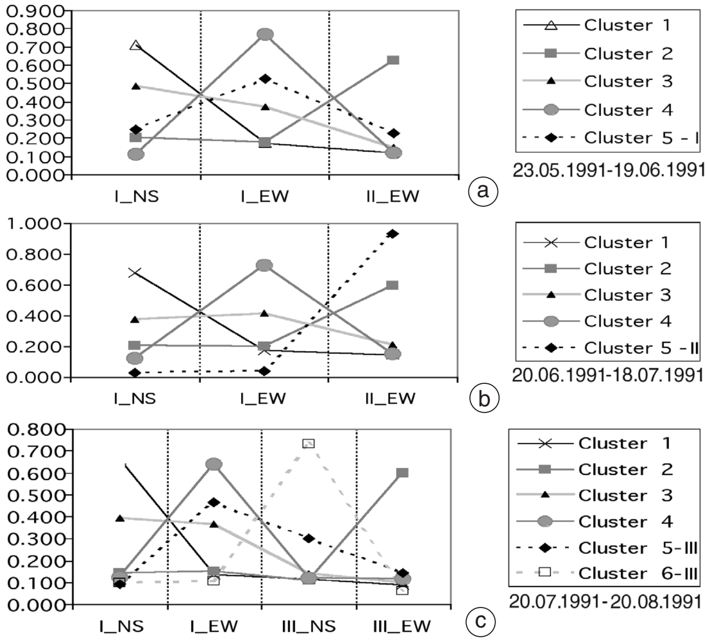

Fig. 4a-c. The distribution of relative amplitudes of signals at the points of measurement produced by the cluster centers of sources for the three independent intervals of monitoring. The Roman numbers designate the points of measurement. NS and EW specify directions of measuring lines.

The data processing is based on the assumption that the ratio of signal components of different measuring lines should remain a constant at a constancy of properties of environment and geometry of source of a signal. In this case, it is possible to take advantage of cluster analysis for determination and classification of sources of signals. So the detected signals were subjected to the standard cluster analysis using the *k*-means clustering algorithm. The metrics of space-L2, the dimension of space, as clearly seen from fig. 4a-c is 3 or 4. We used for clustering ratio of amplitude of a signal on a line to the sum of modules of amplitudes of signals on all lines. For an estimation of time-stability of the received results the period of observation was broken into three intervals and clustering was carried out formally for each interval independently.

Results of data processing are given in table I and fig. 4a-c. We can see the distribution of relative amplitudes of signals for the cluster centers of sources on the points of measurement for the three independent intervals of monitoring (fig. 4a,b and c). As is clearly seen, some sources exist throughout the observation (1, 2, 3, 4), some sources arise and disappear (5-I, 5-II). In table I the clusters designated by simple numbers exist throughout the period of observation. The clusters with numbers containing an interval number exist only in this given interval of observation. The clusters are characterized by *F*-value, *p*-level and number of signals for more detailed representation of the clustering.

As is seen in fig. 4a-c and table I, the sources of signals are well clustered. For all cases the *F*-value (the ratio of the between-groups variance over the error variance) is more than 2000.

The distribution of relative amplitudes of signals for the cluster centers of sources clearly demonstrates the local nature of the signal sources. This result appeared unexpected in some respects. If the threshold of selected signals is lowered, we see the greater number of

Table I. The result of cluster analysis of electrotelluric signals with steep fronts (see the text). Numbers of points are designated by the Roman numbers, EW and NS specify orientation of measuring lines.

	Statistical significance		Relative amplitudes of signals for the cluster centers					
23.05.1991-19.06.1991								
Point_component	*F*	*p*	1	2	3	4	5_I	
I_NS	4205	0.000	0.712	0.483	0.110	0.200	0.245	
I_EW	4218	0.000	0.171	0.370	0.770	0.178	0.527	
II_EW	2002	0.000	0.117	0.147	0.120	0.623	0.227	
Number of signals			587	855	519	405	726	
20.06.1991-18.07.1991								
Point_component	*F*	*p*	1	2	3	4	5_II	
I_NS	6811	0.000	0.678	0.375	0.123	0.206	0.030	
I_EW	7462	0.000	0.177	0.416	0.726	0.201	0.037	
II_EW	13641	0.000	0.145	0.210	0.151	0.593	0.932	
Number of signals			663	644	715	866	1570	
20.07.1991-20.08.1991								
Point_component	*F*	*p*	1	2	3	4	5_III	6_III
I_NS	4889	0.000	0.658	0.395	0.122	0.142	0.091	0.100
I_EW	4350	0.000	0.136	0.364	0.640	0.151	0.466	0.107
III_NS	4244	0.000	0.118	0.140	0.120	0.108	0.300	0.730
III_EW	2494	0.000	0.088	0.101	0.117	0.599	0.144	0.063
Number of signals			541	875	1024	380	1736	561

signals of close located sources, but not the greater number of sources. Detection of the same cluster of sources using formal cluster analysis for different time intervals and different measuring arrays adds strength to the hypothesis that these local sources really exist.

To clarify the relations between the cluster analysis results and the parameters of sources of signals, we estimated parameters of a source for the centers of clusters (fig. 5). The results were obtained using the data of points 1 and 3 (20.07.91-20.08.91), all estimations were made on the basis of the assumptions of homogeneous medium and a position of sources near to the Earth surface. No sources could not be approximated by a model of a point source, but all sources with a small error were approximated by a model of a dipole. As is clearly seen from fig. 5, all sources are located in immediate proximity to the measuring arrays. It should be noted that sources for clusters 1 and 2 have very similar position and orientation.

Dynamics of every cluster can be estimated using several characteristics. For the arbitrary interval of time it is possible to obtain estimations of number of signals, dispersions of spatial characteristics of the cluster sources, average amplitude of signals, the maximal amplitude of signals. The corresponding calculations testify that these characteristics behave independently of one another.

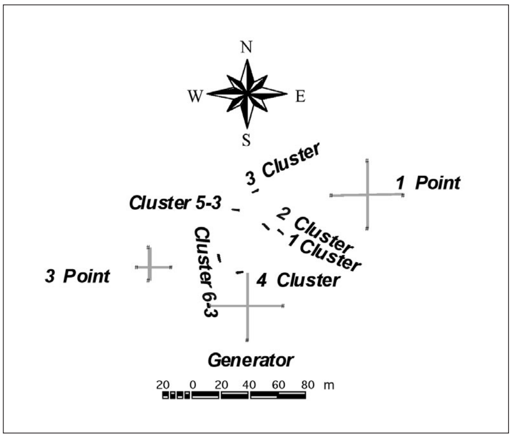

Fig. 5. The disposition of electric dipoles approximating a field of sources of the recorded signals for the third interval of observation. The disposition of measuring and generating lines are also shown in the figure.

As an example let us consider the daily occurrence of the signals for the period including the largest aftershock ($M = 6.2$, 15.06.91). Figure 6a-f shows the variations of average daily rock resistivity and number of ULF signals for the five clusters at the period from 23 May up to 19 June 1991. The plot in the top right corner in (fig. 6a) shows time dependence of the *U*/*I*, which is proportional to resistivity. On other fragments of (fig. 6b-f) variations of the number of signals for each of five clusters are given. We see that the sources radiate practically continuously and on some days there are anomalies exceeding an average level approximately in four time. The clusters behave rather independently of one another, showing the absence of dependence on the external magnetotelluric field. Sometimes there are synchronous anomalies, in our opinion connected with the change in mode of deformation of the rocks. The dynamics of clusters 1 and 2 (which have sources with similar position and orientation) are quite similar. Indeed, the moments of all extremes coincide with each other, although the amplitudes of anomalies are dissimilar. Dynamics of 3 and 4 clusters (which have sources sharply differ by position and orientation from sources of 1 and 2 clusters) sharply differ from dynamics of 1, 2, 5_I clusters.

During observation each day there were many aftershocks of different magnitudes with different distances from point of observation. To compare the dynamics of sources with dynamics mode of deformation near the point of measurement we calculated *a posteriori* theoretically estimated value of changes in mode of deformation. Estimation of a theoretical variation of deformation in point of observation was made using the catalogue aftershocks produced by the group of Dr. Aref'ev, and theoretical formulae obtained by Dobrovolsky (1991). Figure 5 shows the results of corresponding calculation.

We propose that the deformation from every aftershock is independent from each other, allowing us to make daily estimations of components of deformation by summing up the square

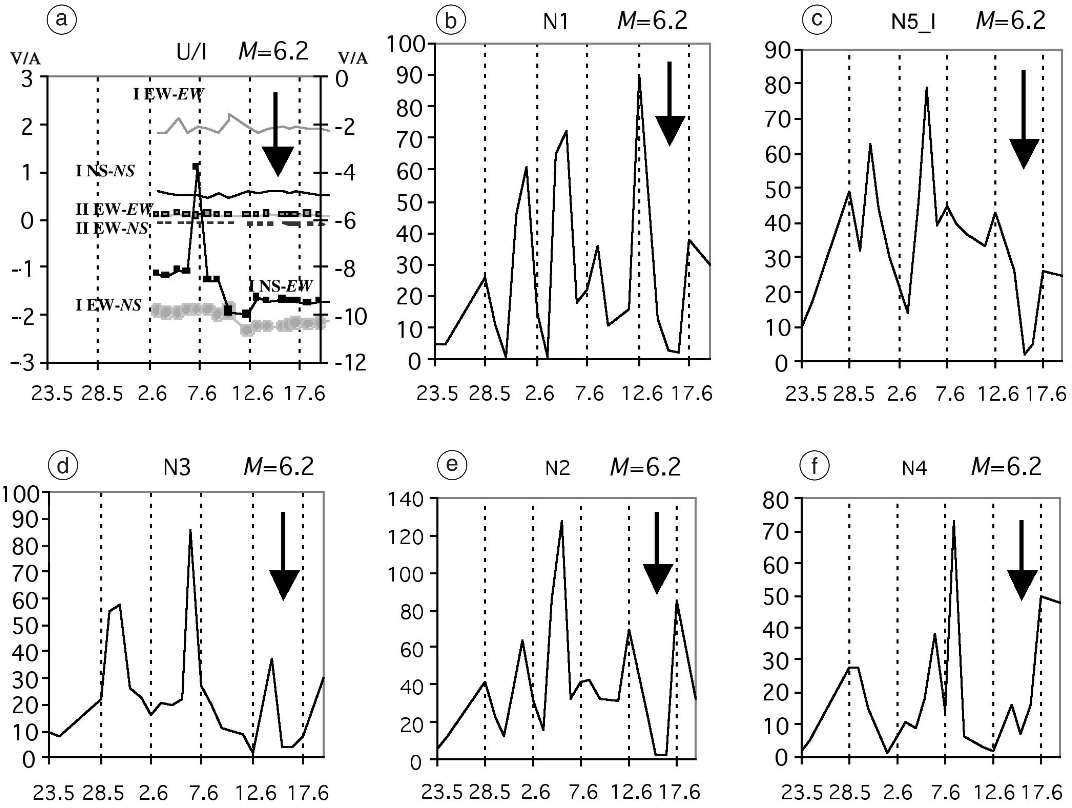

Fig. 6a-f. Variations of the average daily rock electroconductivity and numbers of ULF signals for the five clusters at the period from 23 May up to 19 June 1991. The Roman numbers designate the points of measurement. Here NS and EW specify the directions of measuring lines, whereas the italic *NS* and *EW* specify the directions of generating lines. The Arabic numbers specify the clusters. The arrow indicates the time of the aftershock.

of amplitudes of components for all aftershocks which occurred this day. To take into account the duration of aftershock preparation times, we used phenomenological estimation for duration of a short-term precursor (Dobrovolsky, 1991) as weight at summation. As for the overwhelming majority of events duration of a short-term precursor is less than a day, this procedure seems to be appropriate. However, for the aftershock of June, 15 with $M = 6.2$ the duration of a short-term precursor is 4.7 days. Thus anomaly June, 15 would spread till June, 11. But we have not reflected it in the diagram because of uncertainty of the law of change in amplitude of a short-term precursor in time and for preservation of uniformity of processing. From fig. 7a-c a significant excess of all calculated components at June, 15 is clearly seen. In view of this, it is possible to consider a synchronous local maximum of the number of signals for clusters 1, 2, 5_I at June, 12 as a possible precursor for aftershock June, 15. The level of theoretically estimated value of the changed mode of deformation caused by other aftershocks this day is low (fig. 7a-c). Anomaly in occurrence of the signals in the cluster 1 makes about 400 % in comparison with the previous and next days. Anomalies of the signals in clusters 1, 2 and 3

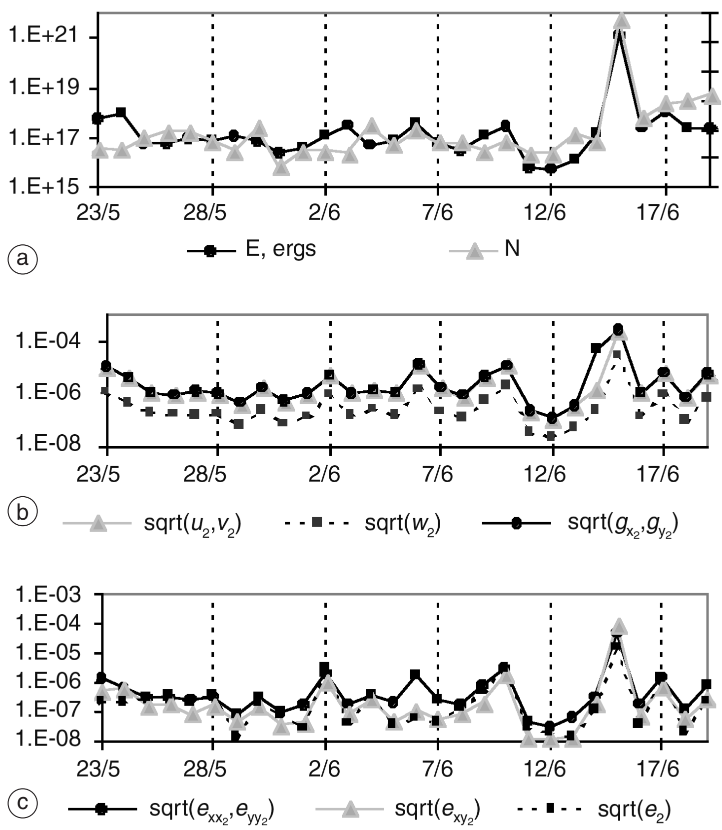

Fig. 7a-c. Average daily variations of the number occurrence and energy of the earthquakes (a), and a posterior theoretical estimates of average daily anomalies in the displacement and inclination (b), and in the linear and volumetric deformations (c) at the observation point. Here u, v and w are components of displacement, g_x and g_y are the anomalies of components of inclination; e_{xx}, e_{yy} and e_{zz} are the linear and volumetric deformations before the earthquake (see the text).

at June, 12 is anticipated and accompanied by a change in resistivity on several measuring lines, that is the additional argument for their connection with changed mode of deformation. The day of the strongest aftershock is marked by a local minimum of quantity of signals for all clusters. Since May, 23 in clusters 1, 2, 5_I synchronous fluctuations of gradually increased amplitude fluctuations are noticed, similar data were obtained by Meyer and Teisseyre (1988). We propose that these facts are indirect evidence of the relation of changed mode of deformation with a process of preparation of aftershock June, 15.

3. Reliability of establishing the correspondence between the signal and its source: a practical example

Some critical remarks on the empirical earthquake prediction developed by the VAN group are not eliminated by acceptance of a hypothesis of a local origin of the precursor's sources. These are remarks concerning reliability of the data of monitoring electrotelluric field.

Opponents assert that the VAN group cannot identify and eliminate ambient natural and artificial geoelectrical noise sources before claiming to have observed geoelectrical precursors of distant earthquakes (Chouliaras and Rasmussen, 1988; Gruszow *et al.*, 1996). Most scientists consider that rules for discriminating between alleged earthquake precursors and noise proposed by VAN are inadequate (Chouliaras and Rasmussen, 1988; Gershenzon and Gokhberg, 1993; Pham *et al.*, 1998; Uyeda *et al.*, 2000).

The problem is complex and breaks down into several aspects. For the sake of convenience, electrotelluric monitoring can be provisionally divided into a «technical stage», where relations between the electric field and its source are considered, and a «prediction stage», where relations between the signal, its source and parameters of impending earthquake are studied.

Let us consider the problems concerning the reliability of detection a signal, discrimination between signal and noise, and an estimation of characteristics of the signal source. The data of electrotelluric monitoring have the additional degree of uncertainty in relation to the data of other methods recording local variations. The area of gathering of the information depends on the intensity of source, and it is practically unlimited. Signals with steep fronts can be ionospheric in origin (*e.g.*, SSC), they can also be generated by a number of other sources of industrial noise. In a vicinity of measuring array, as a rule there are some numbers of sources of the natural electric field (oxidation-reduction, membrane, a piezoelectric or electrokinetic nature), which may or may not be connected to the process of preparation of earthquake. Recorded signals can be a reflection of changed resistivity of the medium (Yamazaki, 1974, 1975) in an external field of ionospheric or terrestrial origin. And last but not least, the electrodes, which are used for measurements can be sources of false anomaly signals due to instability and high sensitivity of potential of a double electrical layer to the numerous external influences. All this together with the non formalized method of isolation of precursor signal causes natural mistrust of the scientific community in the results of monitoring.

We shall notice that the methods, which are not using manual isolation of a signal (Lukk *et al.*, 1996), based on an analysis record as process, can also appear ineffective in this case. It is connected by that on a measuring line we record the signals determined by various pro- cesses, and the common views on the dynamics of such mix hardly have physical sense. Spectral estimations used in such approaches are also unsuitable means for detection and an evaluation of parameters of small signals with steep fronts.

Lacking clear morphological distinctions between the signals, methods of spatial filtration are the only means of separation of sources by spatial localization and scale.

As mentioned above, a set of long and short lines having the common electrodes is not effective for detection of signals of local sources. Our approach to the detection of signals described in the previous section is appreciably reducing these gaps. Allocation of the signal from the local source more reliably because four independent lines record the signal, and for its detection the formalized procedure of a spatial filtration is used. Moreover, reliability of the result of monitoring also increases since the significant number of signals with the same spatial structure can be analyzed instead of one signal. Thus, we are going from monitoring signals to monitoring characteristics of their sources. There are two questions. How far can we classify and identify different clusters of sources? Can we estimate position of a source?

For an estimation of to what extent the ratio a component of a field recorded on two orthogonal lines in one point of measurement allows us to estimate a direction on a point source in inhomogeneous medium a special field experiment was carried out. At the point of measurement two orthogonal measuring lines in length of 6 m were located. At the point of measurement the artificial heterogeneity with infinite resistance (L = 1.5 m, W = 0.8 m, D = 0.8 m) was created. On two orthogonal measuring lines we measured signals of the controllable point source being moved by the operator along radial profiles from the center of array. (The second point electrode was grounded at a distance 10 times exceeding the maximal distance between the center of measuring array and the first electrode). This kind of survey may be termed the calibration of measuring array. This array establishes the correspondence between the image of source and its real position for the cho-

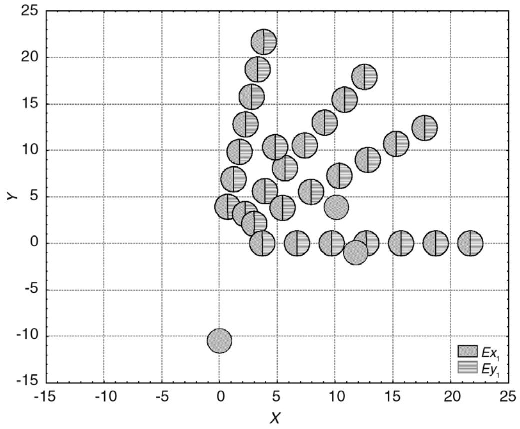

Fig. 8. Calibration of the standard measuring array (two-component orthogonal dipoles centered at the point (0, 0) by using point source placed at the point (*x, y*)). The circular diagram at each given point of the tablet shows the relation between the signal components of measuring array produced by a point source located at this point.

sen type of a source. Figure 8 gives the results of the carried out calibration of measuring array. Apparently the influence of heterogeneity does not allow estimation of a direction on a point source, and the ratio of the orthogonal components remains practically constant under changes in an azimuth of a source in a range of 80°.

From here it is possible to draw a conclusion on the need for multivariate observations for an estimation of source's parameters in the inhomogeneous medium. The symmetric measuring array offered for this purpose is shown in (fig. 9). For realization of measurements of a set of the first and second derivatives of potential of electric field specially developed equipment was used. The measuring system consists of blocks of preamplifiers and a digital system of recording (ADC 10 bit, amplification factors from 0.25 up to 8, automatic compensation of zero's shift, sample rate 200 Hz).

Figure 10 presents the results of the calibration of this measuring array at the same point under the same conditions as calibration of standard measuring array. We see one of several gauge maps which shows the relational values of angles between components of a vector field measured by two pairs of two orthogonal measuring lines. It seems clear that opportunities for an estimation of position of a point source here are much greater. The given array uses advanced methods of spatial filtration and gives us more

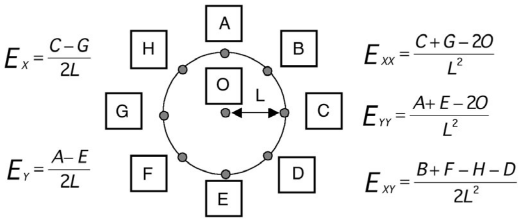

Fig. 9. The arrangement of electrodes of the proposed «nine-points» array. Measured finite-difference approximation for the first and second derivative of the electric potential are also shown in the figure. Latin letters designate potentials suitably located electrodes.

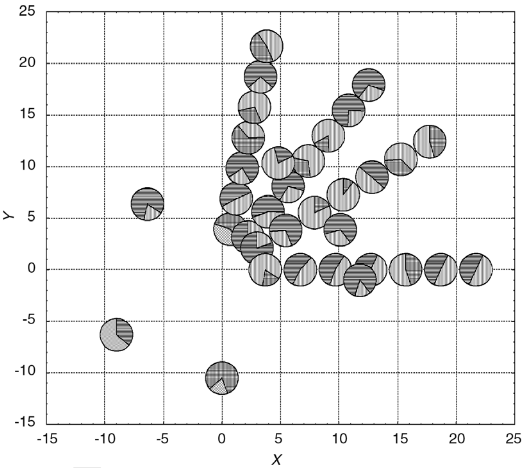

Fig. 10. Calibration of the proposed nine-electrode measuring array centered at the point (0, 0) by using point source placed at the point (*x*, *y*). The circular diagram at each given point of the tablet shows the relation between the signal components of measuring array produced by a point source located at this point (see text).

opportunities for reliable detection of signals and clustering of its sources on the basis of spatial properties. Pairing such arrays together, application of the formalized procedures of detection of signals with steep fronts and clustering of its sources will trace the dynamics of signal sources and with the help of calibration of measuring array estimate the source parameters in the inhomogeneous medium.

4. Reliability of establishing the causal relation between the precursor and the impending earthquake: a general approach

The model of local origin of signals with steep fronts permits us to explain almost all experimental facts which are seemingly in contradiction with the model of a source in the epicenter of future earthquake (see the Section 1). Local precursor is less rigidly connected with the preparing earthquake. This also clarifies the gradual changes in terms of a prediction of the future earthquake made by the VAN group from 6-115 h (Varotsos and Alexopoulos, 1984a) to one-two month (Varotsos *et al.*, 1996). The notion of local origin of signals removes the requirement of one-to-one dependence between signals and earthquakes, what also contradicts experimental data. The model of local sources easily explains the appearance of signal selectively on some isolated lines within the confines of a given station (Noto, 1933; Yoshimatsu, 1957; Varotsos and Alexopoulos, 1984a,b, 1987; Miyakoshi, 1986; Varotsos *et al.*, 1988, 1993, 1996; Varotsos and Lazaridou, 1991), and paradox with a lack of synchronism of signal occurrences on different lines in some cases (Varotsos and Alexopoulos, 1984b).

It should be noted that the causal relation between precursory signal and preparing earthquake is a very weak point in any method of

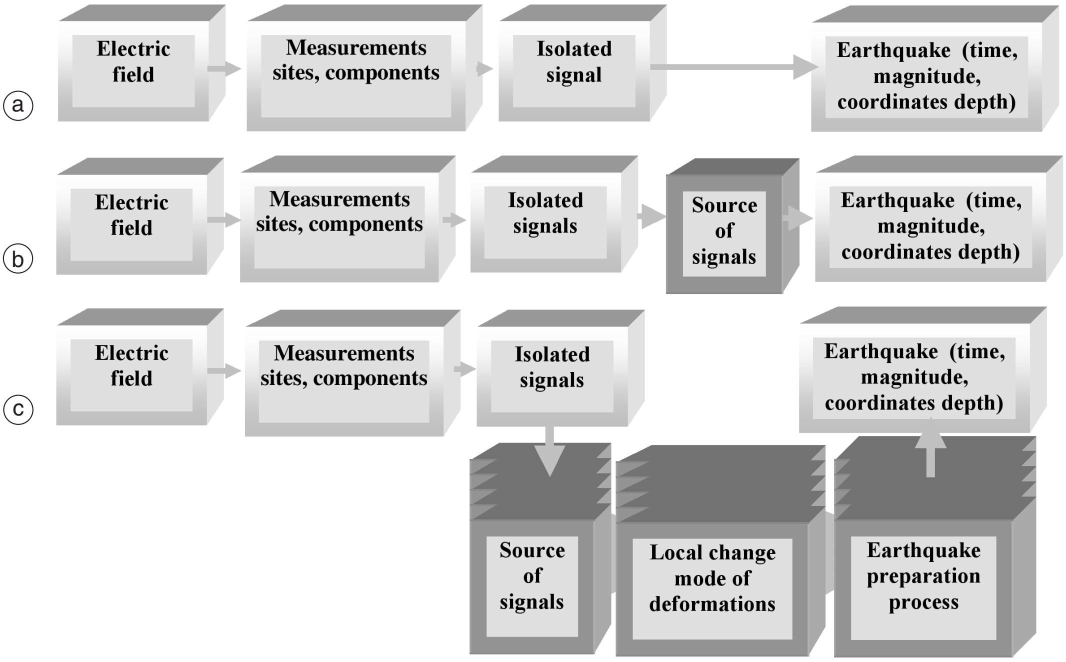

Fig. 11a-c. a) Standard and (b) new proposed empirical schemes of the forecast. c) The so-called theoretical scheme is also presented in the figure (see text).

prediction of the earthquakes, and most notably of predictions based on the control of local characteristics of medium. Figure 11a-c illustrates the situation. The top panel (fig. 11a) presents the standard empirical scheme of prediction on the basis of monitoring of local characteristics of the medium. At such an approach an attempt is made to establish some empirical relations between two events that have occurred at different times and in different places. This relation can be proved only statistically because the material objects responsible for this connection are not considered at all. There are the source of the signal, local changed mode of deformation that is cause of signal, and regional changed mode of deformation, determined by process of preparation of earthquake. The theoretical prediction (bottom panel fig. 11c) includes definition of parameters of a source in many points of region, calculation using them of the values of local changed mode of deformation, an estimation of dynamics of regional changed mode of deformation and conclusion on probable parameters of impending earthquake (place, time, magnitude).

Transition to studying the relation of dynamics of a signal source with changes in the local and regional mode of deformation is the transition from a level of statistical comparisons on a level of research of physical relationships. The theoretical prediction is now impossible due to the uncertainty of the mechanism of source formation and an insufficient degree of development of the theory of preparation of earthquake. However, the standard empirical scheme of the prediction can be improved (see the fig. 11b, middle panel). Inclusion in the scheme of predicting the cause of the signal, *i.e.* its source gives a material object for research. Reliability of detection of a precursor is increased due to use of the formalized statistically proved criteria of detection. Empirical comparison of dynamics changes the characteristics of a source even in one point of observation with parameters of earthquake seems to be more fruitful, because this is a comparison of characteristics of process with characteristics of the event, which occurred during this process.

5. Conclusions

The original method for recognition and monitoring of ULF electrotelluric signals with steep fronts has been presented. The method is based on the idea of spatial filtration taking into account the polarization properties of the signals, and recognition of the clusters of the signal sources using the data of spatial-polarization filtering. These procedures allow us to detect the specific anomalies of the ULF geoelectric field against a noise background through the control of intensification and synchronization of the cluster emissions. In addition, a measuring array is proposed which gives the possibility to realize the method by using the multicomponent measurements in each given point. The multicomponent measurements make it possible to detect the source of an anomalous ULF signal under the real condition of heterogeneous media.

The method may be used in the search for electrotelluric forerunners of earthquakes. As a first step, the method was applied to the study of geoelectric sources associated with aftershocks of the Racha-Djava earthquake (29.04.1991, $M = 6.8$). The local origin of ULF signals with steep fronts has been shown. Namely, these signals are generated by a small number of local zones in the immediate vicinity of the observer (at a range of tens-hundreds meters). The spatial distribution of the sources is rather stable, but the number of pulses per day and their amplitudes may vary several-fold according to the variation of the local stress-strain state of the medium. None of the sources could be approximated by the model of a point source, but all sources with a small error were approximated by the model of a dipole. It is established that overall the sources radiate independent of each other. The remarkable exception is the largest aftershock (15.06.1991, $M = 6.2$). Before this aftershock a synchronous dynamics of the clusters 1, 2 (which have sources with similar position and orientation) was observed, and this event was accompanied by abnormal changes in the electrical resistance of the rock. Dynamics of 3 and 4 clusters (which have sources with different position and orientation) was not synchronous.

Also remarkable is a synchronous minimum of the ULF geoelectric activity at the day of aftershock. I believe that the similar abnormal behavior of ULF signals with steep fronts may be considered a possible electrotelluric precursor of earthquakes.

In conclusion, the well-known difficulty in the study of the electrotelluric precursors is partly associated with pitfalls in the standard phenomenological method of the earthquake prediction. It is usually based on the search for an empirical relationship between the earthquake and precursor electric signal. However, these two events are separated from each other in space and time. The electric signal may be only causally bound with the future earthquake only via an interface agent, namely, through some current sources, which are generated as a result of evolution of the mode of deformation of the rocks in the course of the earthquake preparation. According to this line of reasoning, attention was focused on the careful detection of the sources responsible for the electrotelluric signals, and also on the study of relations between the dynamics of electric precursors with the dynamics of the local mode of deformation of the Earth's crust.

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