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THEORETICAL AND EXPERIMENTAL VALIDATION OF SEISMOELECTRICAL METHOD

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ABSTRACT: The main aim of this study is a theoretical and experimental validation of the method based on a recording of the seismoelectrical effect upon excitation of seismic fields by the special non-explosive striker and without an additional source of the electromagnetic field. Signals of seismic and electrical fields were recorded using earthed electric dipoles and seismic receiver with subsequent processing using seismic acquisition system. The frequencies of recorded fields were in the range of 0.1–20 Hz. The observation results of seismoelectrical effect resulted from excitation of the geological section by seismic shocks (a KEM-4 striker) and recording of secondary electrical and seismic fields on the surface by measurements of their cross-correlation function. The activities were performed during July 23–30, 2017 on Bystryansky gas condensate field (Krasnoyarsk Krai, Minusinsk district). The productive deposit was indicated by the maximum coefficient of cross-correlation by three times higher than normal background. 3D maps of the seismoelectrical section were obtained for the first time.

Keywords: Seismic noise, Electrical noise, Cross-correlation, Gas condensate field, Seismic survey.

1. INTRODUCTION

Traditionally, hydrocarbons are explored using a set of seismic surveying methods [1], [2], herewith, the main issue is the challenge of the inverse problem which leads to the fact that only about one-half of wells is productive. Various geophysical methods improve quality of detection of hydrocarbon deposits [3], [4], hence, application of additional data variables of detection and reduction of expenses of surveying is an important and urgent measure.

The first positive results of the application of seismoelectrical method were obtained offshore using towed receiving electrical and seismic cables with simultaneous excitation of deposit by pulsed electrical and seismic field [5], [6]. As already mentioned, this method permits to decrease probability of omitting of productive anomalies by up to four times, however, without intensifying electrical field the propagation depth cannot be higher than 500 m, which significantly complicates its on land application since it requires powerful sources of electromagnetic field (about 100 kW) [7].

Due to insufficient information about propagation velocity of seismic waves, it is impossible to achieve totally synchronous excitation of the productive seam by sources of two types, which decreases significantly sensitivity of the method.

The work [8] reports the first observations of seismoelectrical effect on Bystryansky gas condensate deposit in passive seismic and electrical fields by the recording of cross-correlation function (CCF) and its maximum, cross-correlation coefficient (CCC), in the frequency range of 0.1–20 Hz on the ground surface. The cross-correlation function is calculated as follows:

$$\boldsymbol{R_{ES}(\tau) = \frac{1}{T}\int_{0}^{T} \overline{E}(t)\cdot(t-\tau)dt} \quad (1)$$

where $\overline{E}$ *(t)* and $\overline{S}$ *(t)* are the signals of electrical and seismic receivers normalized to their dispersions; *T* is the time of signal observation, 60-180 s.

This study is aimed at theoretical and experimental validation of the method based on the recording of seismoelectrical effect upon excitation of seismic fields by special non-explosive striker without an additional source of electromagnetic fields.

2. METHODS

Let us theoretically estimate the sensitivity of seismoelectrical method for modifications with and without an additional electrical field.

Comparative ratios of root mean square values are considered as sensitivity:

$$\boldsymbol{\eta = \frac{E_0(t)}{E_1(t)}} \quad (2)$$

where $E_0(t)$ is the field measured on the surface without additional electrical irradiation, $E_1(t)$ is the filed measured on the surface with additional electrical irradiation.

Let us assume that the seismic oscillator operates in pulsed mode with the pulse time $\tau = 5\ \mu s$, the repetition time $T=10$ s and the impact force $F=10^6\ N$. Upon the impact of seismic wave, the surface of reflecting layer will be deformed under the pressure with amplitude:

$$\Delta \mathbf{P} = \frac{FS_\Pi}{4\pi h^2} e^{-\alpha h} |\Pi \alpha| \tag{3}$$

where h is the depth of reflecting layer; α is the coefficient of absorption of the seismic wave by the medium; S_Π is the surface area of reflecting layer.

Under such pressure on the productive seam with the surface area of 10^6 m^2, the seam height $\Delta h=100\ m$, and the depth of $h=2000\ m$, the electrical field with the intensity in the range of $E=0.5\text{-}1\ \mu V/m$ is generated on the ground surface. This is comparative with the amplitude of natural telluric field $E_T \approx 1\ \mu V/m$.

Let us estimate the intensity of electrical field on ground surface by hydrocarbon seam at the depth of $h=2000\ m$ upon excitation by cable with the length of L=3000 m located on the surface of half-space with the conductivity σ_1. The cable ends are earthed. Let us assume that the current across the cable is $J_x = 100A$ at operatioan n frequency of $f = 1Hz$. A productive seam with the conductivity σ_2 in host medium with the conductivity σ_1 is located at the depth h (Fig. 1).

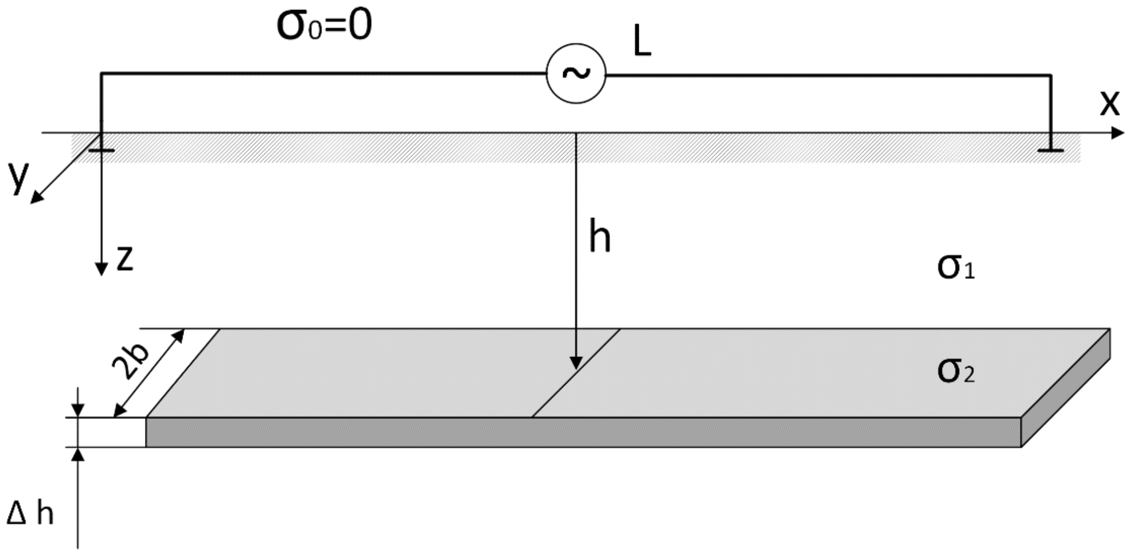


Fig.1 Analytical model for estimation of the influence of an electrical field

The field of the cable earthed at the depth of h can be determined as follows:

$$E_x = \frac{j_x}{\sigma_1} \cdot e^{-\alpha_1 \cdot z} \tag{4}$$

where j_x is the current density in the space created by the earthed cable.

$$J_x = \frac{J}{2 \cdot \pi}\left[\frac{x}{(x^2+y^2+z^2)^{3/2}} - \frac{(x-L)}{[(x-L)^2+y^2+s^2]^{3/2}}\right] \tag{5}$$

α_1 is the attenuation coefficient in the medium with conductivity σ_1 at frequency f;

$$\alpha_1 = \omega \cdot \sqrt{\frac{\varepsilon \cdot \mu}{2}} \left(\left(1 + \left(\frac{\sigma}{\omega \cdot \epsilon} \right)^2 \right)^{1/2} - 1 \right)^{1/2} \tag{6}$$

In the considered variant, when biasing currents can be neglected, that is, $tg\ \delta = \frac{\sigma}{\omega \cdot \varepsilon} \gg 1$:

$$\alpha_1 = \sqrt{\frac{\varphi \cdot \mu \cdot \sigma_1}{2}} \tag{7}$$

$\omega = 2\pi \cdot f$; μ is the magnetic permeability of medium; ε is the absolute dielectric permeability of medium.

Electrical field occurring on the seam surface and penetrating into the seam generates a current which can be estimated as follows:

$$J_c = \frac{1}{n} \cdot \sum_{i=1}^{n} J_{ic}$$

(8)

where n is the number of seam partitioning along the axis y into elemental conducting bands with the width of dy; J_{ic} is the current distribution across the seam for current value dy in the range of $\boldsymbol{y = (-z_1 \div z_1)}$.

The current of each band depends on the penetration depth of electrical field E_x into the seam $\boldsymbol{\delta_2 = \frac{1}{\alpha_2}}$:

$$\boldsymbol{J_{ic} = E_{xi} \cdot \sigma_2 \cdot \delta_2 \cdot dy} \tag{9}$$

where the product $\boldsymbol{\delta_2 \cdot dy}$ is the surface area of cross section of the elemental conductor.

Thus, in the seam area we obtain the secondary magnetic field with the intensity:

$$\boldsymbol{H = \frac{J_c \cdot e^{\alpha_1 \cdot h} \cdot e^{-\alpha 2 \cdot (\Delta h - \delta_2)}}{2 \cdot \pi \cdot h}} \tag{10}$$

where $\Delta \boldsymbol{h}$ is the seam width; $\boldsymbol{\omega = 2 \cdot \pi \cdot f}$ is the frequency of field generated by the cable; $\boldsymbol{\mu_0 = 4 \cdot \pi \cdot 10^{-7}} \frac{\text{Гн}}{\text{м}}$ is the absolute magnetic permeability of vacuum.

Let us determine the intensity of the electrical field in terms of wave resistance of medium – Z:

$$\boldsymbol{E_3 = \frac{J_c \cdot e^{-\alpha_1 \cdot h} \cdot e^{-\alpha 2 \cdot (R - \delta_2)} \cdot Z}{2\pi \cdot h}} \tag{11}$$

Taking into consideration Eqs. (8), (9) and (11), the value of $\boldsymbol{E_3}$ will be about $\boldsymbol{3 \cdot 10^{-7}}$V/m, that is, by an order of magnitude lower than that of natural electhe tromagnetic field of Earth ($\boldsymbol{1 \cdot 10^{-6}}$V/m). Since this additional EMF induced by artificial electrical field from ground surface at very high current in the exciting cable ($\approx$ 100 A) is lower than the intensity of natural electrical field of Earth by about 3.timnes, the issue of reasonability of its application arises.

In terms of physics, several variants are possible of additional EMF upon intensification by artificial electrical field:

a. Reflection at seam boundary;

b. The effect caused by polarization;

c. Recharging of condenser equivalent to productive seam via environment;

d. Generation of current in ambient salt solution under the impact of the electrical field of electrical intensification.

Factor (b) was observed by the authors at Bystryansky gas condensate deposit using differential implementation of the method of induced polarization in passive fields [8].

Therefore, confirming the abovementioned theoretical evaluations, upon on land implementation of the SE method an additional artificial electrical field is not required. Since electrical field on the surface is more integrated into comparison with the seismic field, then the operation does not require for numerous electrical dipoles, for instance, not more than 5 for the distance of 1000 m.

The conclusions on the reasonability of intensification by additional electrical field were verified by experiments on Bystryansky gas condensate deposit in July 2017, this gas field is located at the depth of about 2 km. Geological map of the deposit is illustrated in Fig. 2. A pulsed non-explosive seismic source, model Yenisey KEM-4, was used as an oscillator, the impact force: $10 \cdot 10^5$ N (100 ton-force), the pulse duration: 5 ms, and the repetition time: 10 s.

The electromagnetic field of deposit E(t) was recorded by means of the earthed electrical dipole with the length of 200 m in combination with special digital filters suppressing industrial noises of 80 dB synchronously with recording of the seismic signals reflected from deposit using standard seismic receivers, model SGD-SET/FU, the data of all sensors were recorded by seismic acquisition system, model SGD-SET. 41 seismic receivers were used positioned in 12.5 m, the time of recording: 6 s, the number of received recordings: 10.

Figure 3 illustrates schematically the experimental layout depicting the interaction between seismic and electrical waves of the hydrocarbon deposit. The pulse seismic oscillator 3 exciting the seismic wave 4 was installed on the surface of the studied geological medium 1; on the considered profile the seismic receiver 10 and the earthed electrical dipole 8 were installed connected to the seismic acquisition 9. The electrical 7 and the reflected seismic signals 4 from the productive hydrocarbon seam 2 were recorded. The seismic acquisition system 9 was preliminarily programmed on the basis of initial test signals of seismic source and the time interval was adjusted according to the initial characteristic reflected seismic signals 4. Subsequently, the program operated automatically so that in the repetition period of impacts of the seismic source T the CCC was calculated by Eq. (1).

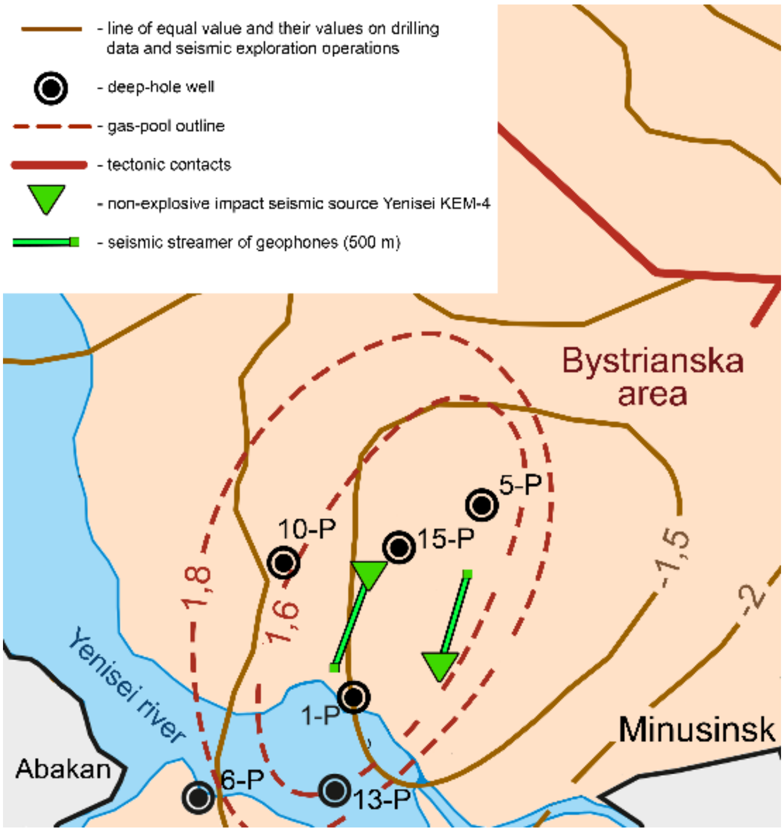


Fig.2 Geological map of Bystryansky gas condensate deposit.

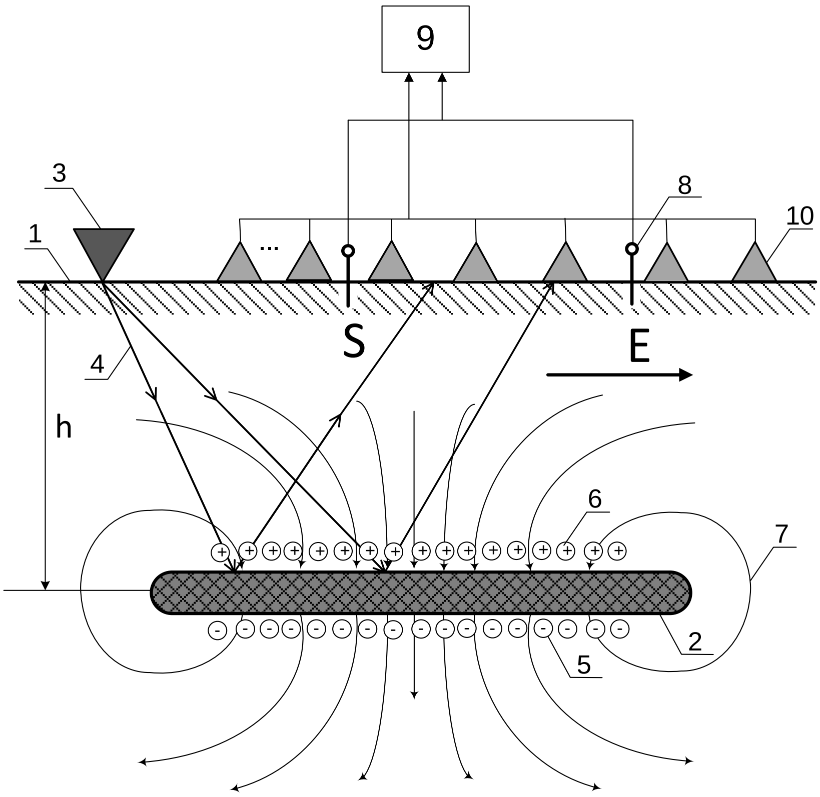


Fig.3 Installation diagram: 1 – ground level, 2 – productive seam, 3 – KEM-4 seismic oscillator, 4 - incident and reflected seismic waves, 5, 6 –charges at deposit boundaries, 7 – electric field of deposit, 8 – electric dipole, 9 – receiving terminal, 10 – seismometer cable

3. RESULTS AND DISCUSSION

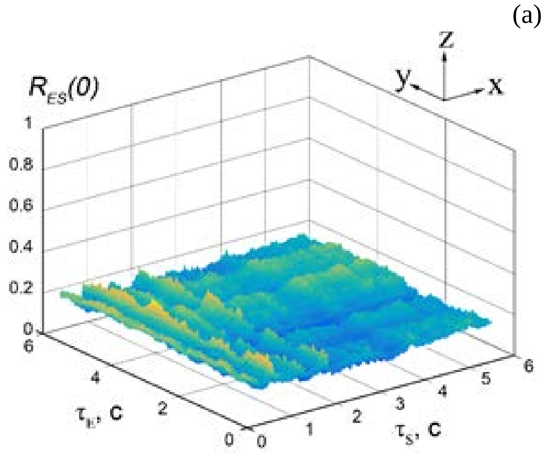
Theoretical estimation showed that sensitivity of the SE method was $\boldsymbol{\eta} = \mathbf{3.3}$, hence, the electrical constituent of about 1 μV/m appeared on the surface of geothe logical section without artan ificial electrical field.

Figure 4 (a, b) illustrates a 3D view of processed data in the normal field (without deposit) and in the anomalous zone (Bystryansky gas condensate deposit, Fig. 2), respectively.

In this case, the *y* axis shows the start time of a signal received form earthed electrical dipole τ_E, the *x* axis shows the start time of a signal received from a seismic receiver τ_S. The *z* axis shows the minimum of cross-correlation function $R_{ES}(0)$, the variable depending on the level of induced electromagnetic radiation.

The normal zone, Fig. 4 (a), in fact, does not contain anomalous reflected peaks in overall area excited by seismic pulses. Similar patterns are obtained for each seismic receiver, which reflects the structure of the geologic section for corresponding seismic trace.

(a)



(b)

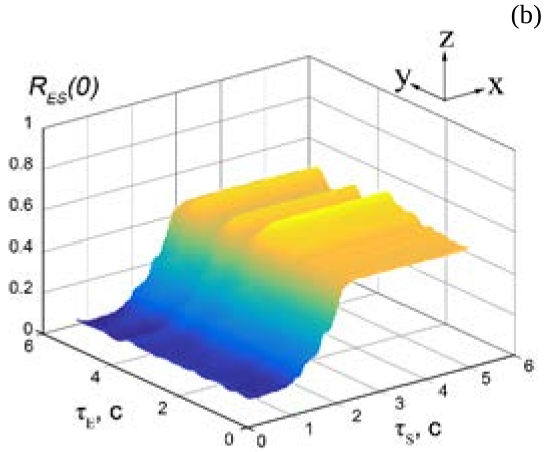


Fig.4 Measured CCC maximum as a function of time interval shift (a) – without a deposit, (b) – Bystryansky gas condensate deposit.

The occurrence of signals *E(t)* from low depths can be attributed to the peculiar generation of electrical charges on ion conducting medium upon sufficiently strong seismic excitation near the ground surface. This is the Debye effect of the first kind, that is, control of conductivity of ion conducting medium by acoustic radiation; synchronous variations of apparent resistivity of the geological section in this case. It has been shown in [9] that three-fold variations of this parameter are possible.

The physical interpretation of the obtained results requires for additional experimental and theoretical analysis beyond the scope of this article.

4. CONCLUSION

In the comparison of SE methods with intensification by artificial electric field, the considered method with excitation only by seismic field significantly simplifies and reduces the expenses of its on-land implementation. It would be reasonable to consider this method in the mentioned modification as semi-active SE method (SE-SAM). It should be mentioned that according to the authors' estimation [5], [6] of active SE method, its on-land implementation would require for at least six large vehicles and pulling off long feeding lines with earthling devices.

On-land implementation of SE-SAM permits to apply conventional seismic survey with standard seismic acquisition system, seismometer cables and additional electrical cable with electrical receiver dipoles.

The following conclusions are therefore drawn::

1. According to theoretical estimation and experimental observations, it is possible to implement the seismoelectrical method (SE-SAM) on land without additional intensification by electrical field involving the simultaneous recording of electrical seismic signals on the surface upon excitation of the geological section only by seismic impacts of the controlled pulsed non-explosive source.
2. Implementation of SE-SAM does not require any additional hardware in comparison with the regular seismic survey; only additional cables with electric receiver dipoles are necessary.
3. Commercial implementation of this method should be supported by numerous experiments at various oil and gas deposits.

5. REFERENCES

[1] Vedernikov G. V, Izuchenie mikroseism pri seismorazvedochnykh rabotakh MOGT dlya prognozirovaniya zalezhei uglevodovorodov [Investigation into microseism upon MOGT seismic survey for forecasting of hydrocarbon

deposits], Abstract, MPK, November 24-26, 2008, SNIIGGiMS, Novosbirisk, 2009, pp. 48-49.
[2] Maksimov L. A., Vedernikov G. V. and Yashkov G. N., Geodinamicheskii shum zalezhei uglevodorodov i passivno-aktivnaya seismorazvedka MOGT [Geodynamic noise of hydrocarbon deposit and passive-active seismic survey CDP method]. Neftegazekspozitsiya, Vol. 6, Issue 45, 2015, pp. 55-57.
[3] Sibgatulin V. G., Peretokin S. A., and Kabanov A. A., Rezonansy gravitatsionnykh prilivov – moshchnyi energeticheskii istochnik geodinamicheskikh protsessov v Zemnoi kore [Resonances of gravitational tides: powerful energy source of geodynamic processes in Earth crust], Tekhnika i tekhnologi. Sibirskii federal`nyi universitet, Vol. 9, Issue 2, 2016, pp. 147-165.
[4] Ageeva O. A., Ispol`zovanie seismoelektricheskikh preobrazovanii v porodakh dlya prognozirovaniya kharaktera nasyshcheniya porovogo prostranstva [Seismoelectrical transformations in rocks for forecasting of saturation pattern of threshold space], Geofizika, Vol. 1, 2008, pp. 16-21.
[5] Mel`nikov V. P., Lisov V. I., Bryukhovetskii O. S. and Bobrovnikov L. Z., Innovatsionnaya geofizika: binarnye tekhnologii pryamykh poiskov mestorozhdenii poleznykh iskopaemykh [Innovative geophysics: binary technologies of direct prospecting of mineral deposits. Ch. 1]. Inzhener-neftyanik, Vol. 1, 2011, pp. 47–51.
[6] Berg A. E., Tehnologija i opyt primenenija stanovlenija jelektromagnitnogo polja pod vozdejstviem sejsmicheskogo obluchenii (SPSO) pri poiskah mestorozhdenij uglevodorodnogo syr'ja [Technology and Experience of Application of Electromagnetic Transient Buildup Affected by Seismic Radiation (TBSR) in the Search for Raw Hydrocarbon Deposits in conditions of shelf], Materials of the X-th international geophysical scientific-practical seminar «The application of modern electrical exploration technologies in prospecting of mineral deposits», St Petersburg, 2012. pp. 35-39.
[7] Berg A. E., Method of Seismo-Electromagnetic Detecting of Hydrocarbon Deposit, US Patent No. 7330790, October, 2005.
[8] Shaidurov G. Y., Kudinov D. S., Potylitsyn W. S., Kokhonkova E. A. and Shaidurov R. G., The First Observation Results on Seismoelectric Effect and Induced Polarisation on Gas Condensate Field in Natural Noise Field of the Earth, Apparatus and Systems of Exploration Geophysics, Vol. 1, 2016, pp. 81–88.
[9] Trigubovich G. M. and Epov M. I., New opportunities for electromagnetic reconnaissance, Abstracts of the report of the scientific-practical conference on November 24-26, 2008, SNIIGGiMS, Novosibirsk, pp.16-19.