Registration of natural emission of hydrocarbon deposits on the basis of two-frequency signals

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Abstract. The article presents the results of modelling and experimental studies on the method of registration of natural emission of hydrocarbon deposits on the basis of two-frequency signals. The application of natural emission registration of hydrocarbons for accuracy increase of electromagnetic methods is substantiated. The dispersion dependences of the combination terms of the tensor of the geological environment over hydrocarbons are analyzed in a wide range of frequencies of the signals used. The frequencies of electron cyclotron resonance and electron plasma resonance have been determined, that allow to distinguish hydrocarbon deposits against the background of other objects. The results of field measurements of the proposed method at Vostochno-Drozdovskoye oil field and Osipovichy gas storage facility are given. The application of multiple illumination frequencies is proposed to improve the information capability of the search methods and the accuracy of hydrocarbon boundary determination.

1 Introduction

Geophysical prospecting plays a big role now, for example to identify hydrocarbon deposits using the existing models for their exploration [1]. Electromagnetic prospecting and monitoring methods are applied for prospecting various types of minerals, for environmental studies because they have advantages over other prospecting methods such as productivity, efficiency. There are also challenges for them, such as the complexity of analyses due to different data acquisition conditions, noise levels and the influence of subjective human factors [2]. Numerous factors must be considered by solving search problems, such as the effect of particle ionisation on the effect of an electromagnetic wave (EMW) on the anisotropic medium (AM) over hydrocarbons [3].

Development of aerospace methods, equipment and systems for solving remote sensing problems in the field of oil and gas complex, processing of aerospace data streams, monitoring of objects, creation of digital maps, three-dimensional models of terrain areas for the oil and gas industry are considered in these studies [4-5].

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In the article [6] geophysical parameters of the Earth's crust were analysed on the basis of the method of depth probe with the use of powerful explosions and dependences of the presence of hydrocarbons on the studied geological profile on the parameters of the Earth's surface were obtained.

Modelling issues and the level of interpretation of measurement data play an important role for geophysical prospecting [7]. Seismic prospecting provides high-resolution imaging of geological profile structures for the discovery of a wide range of mineral deposits [8]. The results of field studies at Marmovichskaya and Geologicheskaya deposits on the basis of measurement of phase components of surface impedance are given for EMV exposure in the mode of amplitude-frequency modulation. The results of field measurements at Marmovichskaya and Geologicheskaya deposits on the basis of measurement of phase components of surface impedance are given for exposure to electromagnetic waves in the mode of amplitude-frequency modulation.

2 Research methodology

The purpose of research is to develop a method of search with registration of natural emission of hydrocarbon deposits on the basis of two-frequency signals. This mode takes into account not only the effects of the harmonic EMW on the AM, but also the natural emission of hydrocarbon deposits. As a result, a two-frequency signal is formed, the study of which is of theoretical and practical interest in the search for solutions for the implementation of new and modernisation of existing electromagnetic methods for the separation and delineation of oil and gas fields, taking into account the parameters of the two waves.

A hydrocarbon deposit can be thought of as a resonant system that emits a tonal oscillation. This signal can be represented as a harmonic electromagnetic wave that acts on a surface wave in the longitudinal direction of the «air-background medium» interface. The result of the superposition of these waves presents a two-frequency electromagnetic wave interacting with the anisotropic medium over hydrocarbon deposits.

Another example of this mode of interaction is the unintentional or intentional influence of a tone signal on the basic characteristics of the studied electromagnetic field produced by a surface wave. Both reflective characteristics of the geological profile above hydrocarbon deposits when probing with a two-frequency signal and anomalous effects of the electric field strength at alternative (with opposite results) frequencies are investigated on the basis of modelling the interaction of electromagnetic waves with various anisotropic media and analysis of the modes of application of two-frequency interaction.

Let us consider the interaction of an electromagnetic wave with amplitudes E_1 and E_2 with the medium above a hydrocarbon deposit on the route of a geological profile of radio wave propagation in the form of an oblique incidence of a plane electromagnetic wave with vertical polarisation in an air medium with parameters ε_0, μ_0, σ_0 (dielectric constant, magnetic constant, conductivity) on an unbounded anisotropic medium having different impedance along the coordinate axes.

The relations between the components of the electric and magnetic field strengths are determined taking into account the components of the dielectric permittivity of the medium over hydrocarbon deposits, allowing to increase the informativeness of search and identification methods.

$$\begin{cases} \dot{\varepsilon}_1 = \varepsilon_r \dfrac{\tilde{\omega}_1}{\omega_2} + \sum\limits_{i=1}^{2} \left\{ \begin{array}{l} \dfrac{\omega_{pi}^2 \tilde{\omega}_1}{\omega_2} \dfrac{\omega_{hi}^2 - \tilde{\omega}_1^2 - \nu_i^2}{(\nu_i^2 + \omega_{hi}^2 - \tilde{\omega}_1^2)^2 + 4\tilde{\omega}_1^2 \nu_i^2} - \\ -j\left[\dfrac{-\varepsilon_r k_E (1-k_\omega)\sin\alpha t}{1 + k_E \cos\alpha t} + \dfrac{\sigma_r}{\omega_2 \varepsilon_0} + \dfrac{\omega_{pi}^2 \nu_i}{\omega_2} \dfrac{\tilde{\omega}_1^2 + \nu_i^2 + \omega_{hi}^2}{(\nu_i^2 + \omega_{hi}^2 - \tilde{\omega}_1^2)^2 + 4\tilde{\omega}_1^2 \nu_i^2} \right] \end{array} \right\}, \\ \dot{\varepsilon}_2 = \sum\limits_{i=1}^{2} \left\{ \dfrac{\omega_{pi}^2 \omega_{hi}}{\omega_2} \dfrac{\omega_{hi}^2 - \tilde{\omega}_1^2 + \nu_i^2}{(\nu_i^2 + \omega_{hi}^2 - \tilde{\omega}_1^2)^2 + 4\tilde{\omega}_1^2 \nu_i^2} - \dfrac{2j\tilde{\omega}_1 \nu_i \omega_{pi}^2 \omega_{hi}}{\left[(\nu_i^2 + \omega_{hi}^2 - \tilde{\omega}_1^2)^2 + 4\tilde{\omega}_1^2 \nu_i^2 \right] \omega_2} \right\}, \\ \dot{\varepsilon}_3 = \varepsilon_r \dfrac{\tilde{\omega}_1}{\omega_2} + \sum\limits_{i=1}^{2} \left\{ \dfrac{\omega_{pi}^2 \tilde{\omega}_1}{\omega_2} \dfrac{1}{\nu_i^2 + \tilde{\omega}_1^2} - j\left[\dfrac{-\varepsilon_r k_E (1-k_\omega)\sin\alpha t}{1 + k_E \cos\alpha t} + \dfrac{\sigma_r}{\omega_2 \varepsilon_0} + \dfrac{\omega_{pi}^2 \nu_i}{\omega_2} \dfrac{1}{\tilde{\omega}_1^2 + \nu_i^2} \right] \right\}. \end{cases} \quad (1)$$

Where $\dot{\varepsilon}_1$, $\dot{\varepsilon}_2$, $\dot{\varepsilon}_3$ – tensor component; ε_r, σ_r – dielectric capacity and conductivity; ε_0 – dielectric constant; ω_{pi} – plasma frequency; ν_i – particle collision frequency; ω_{hi} – gyrotropic frequency, $\tilde{\omega}_1$ – frequency component depending on the frequencies of two signals ω_1 and ω_2, k_E and k_ω – coefficients of the ratio of amplitudes and frequencies of electromagnetic waves, α – difference between two frequencies.

Each component of the tensor has a complex functional dependence and is generally determined by the characteristics of electrons and ions. To improve the accuracy of electromagnetic prospecting methods, a combination of process modelling results, field measurement errors, data processing and interpretation of geophysical tests play an important role. Oil and gas deposits are determined based on media layering over deposits and characteristics influence of the geological profile over hydrocarbon deposits on the electrodynamic characteristics of the anisotropic medium and on the detection results.

Modern electromagnetic methods of searching for hydrocarbon deposits require an increase in the level of interpretation reliability of electrical exploration results. Application of probing signals with variation of electromagnetic wave frequencies f_1 and f_2 allows to perform high-precision estimations of transformations of all spectral signal components and all kinds of nonlinear manifestations when electromagnetic waves impact on anisotropic medium.

Specific condition of the geological profile of the anisotropic medium is reflected in the value of probing signals over the investigated area. For such interaction the experience is used at influence (unintentional or intentional) of a tone signal on electrodynamic response of the studied electromagnetic field on the basis of data of hydrogeological researches and forecast of oil-bearing capacity of oil and gas complexes on modern hydrogeological requirements, on radioactivity of underground sources. Such conditions lead to the formation of complex ionic inclusions of semiconducting character in the region over hydrocarbon deposits, which have increased thermoelectronic emission for a temperature of 20ºC. Research in geophysical prospecting is carried out using remote sensing and aerospace systems, is used in monitoring oil and gas area. The oceanological and climatic conditions of maritime territory are particularly dangerous to the use of drilling operations due to very low temperatures, dense fog and strong gale force winds. This increases the modelling accuracy requirements for the reliability of electrical exploration.

The theoretical analysis of the tensors (1) has been carried out based on study of the frequency characteristics of the total and difference sideband components $\mathrm{Re}\,\varepsilon_R = \dot{\varepsilon}_1 + \dot{\varepsilon}_2$

and $\mathrm{Re}\,\varepsilon_R = \dot{\varepsilon}_1 - \dot{\varepsilon}_2$. The study of frequency dependences shows the transformation of combined tensor elements depending on the variation of coefficients k_E and k_ω. The sign inversion for the real and imaginary components indicates in this case the manifestation of resonance properties of the anisotropic medium to the influence of electromagnetic waves.

The range of electron and ion concentrations ($N_1 = 10^{15}\mathrm{m}^{-3}$, $N_2 = 10^{17}\mathrm{m}^{-3}$), frequency range ($10^4 - 10^{10}$) Hz, medium conductivity σ_r = 10^{-3}S/m, dielectric permittivity ε_r=1–30, particle collision frequency $\nu_i = 2 \cdot \pi \cdot 10^9$ rad/s were considered in the analysis.

The introduction of particle ionization coefficient $k_u \gg 1$ (ratio of ion concentration to electron concentration) in the analysis is justified by the data of studies of test samples of surrounding formations taken from anisotropic medium over hydrocarbon deposits, indicating the excess of ionic currents due to an increase in the number of ions in the medium.

3 Results

It is found that the frequency of the electron cyclotron resonance $f_{2Ц}$ (the point of transition through zero to the left along the x-axis) is within 200kHz for ε_r = 3, and with increasing dielectric permittivity the resonance properties are expressed insignificantly (Figure 1). The range of k_ω and k_E coefficients variation is chosen within ($10^{-6} - 10^{-1}$). Of interest is the frequency $f_2 = 100$ kHz at which the steepness of the characteristic is changed. The electronic plasmon resonance frequency $f_{2П}$ (the point of transition through zero to the right side along the x-axis) is 500 MHz for ε_r = 3, and with increasing dielectric permittivity the resonance properties are expressed insignificantly.

Of interest is the frequency $f_2 = (10–30)$ MHz at which the steepness of the characteristic is changed with increasing values of $\mathrm{Re}(\dot{\varepsilon}_\mathrm{R}(f_2))$. The diagrams show that anomalous behavior of the electromagnetic wave field strength over hydrocarbon deposits should be expected at frequencies equal to $f_{2Ц}$ and $f_{2П}$. The signal reflection from the anisotropic medium will be observed at all frequencies except the frequencies of resonant interaction. When the amplitude of the high-frequency (HF) signal equals to 0.1 E_1, the interaction effect is more significant at smaller frequency differences $\alpha = 2\pi(f_2 - f_1)$. The difference between the amplitude of the high-frequency signal and the amplitude of the low-frequency (LF) signal by 100 and more times leads to deterioration of the reflective properties of the medium over hydrocarbon deposits and the frequencies at which there will be a decrease in the amplitude of the electric field strength of electromagnetic waves are shifted to higher frequencies. When the amplitude of the high-frequency signal is 10^{-3} E_1 there are no resonance manifestations at $f_{2П}$. At insignificant difference of frequencies of two electromagnetic waves frequency dependences $\mathrm{Re}\,\dot{\varepsilon}_\mathrm{R}$ and $\mathrm{Re}\,\dot{\varepsilon}_\mathrm{L}$ (Figures 1-2) practically do not change, however with decreasing of frequency f_1 the character of interaction changes. When the amplitude of the high-frequency signal is equal to 10^{-6} E_1 the character of the $\mathrm{Re}\,\dot{\varepsilon}_\mathrm{R}$ and $\mathrm{Re}\,\dot{\varepsilon}_\mathrm{L}$ curves does not change, and $f_{2П}$ moves to the high-frequency sphere. When k_ω and k_E decrease, the resonance interaction frequency $f_{2Ц}$ increases, but the frequency $f_{2П}$ decreases. Thus, by using a change in the frequency and/or amplitude of one of the field shaping sources it is possible to 'artificially' change the frequencies of resonant interaction between a complex electromagnetic wave and anisotropic formation over hydrocarbon deposits. This analysis indicates the presence of certain effects when the frequency ratio of the two signals is sufficiently large. In this case, an acoustic signal can be used as one of the electromagnetic waves. The magneto-electric effect with acoustic noise is widely used in the development of radioacoustic locators designed to study meteorological conditions in the troposphere, inhomogeneities in the stratosphere and ionosphere, and can also be used in the implementation of electromagnetic methods.

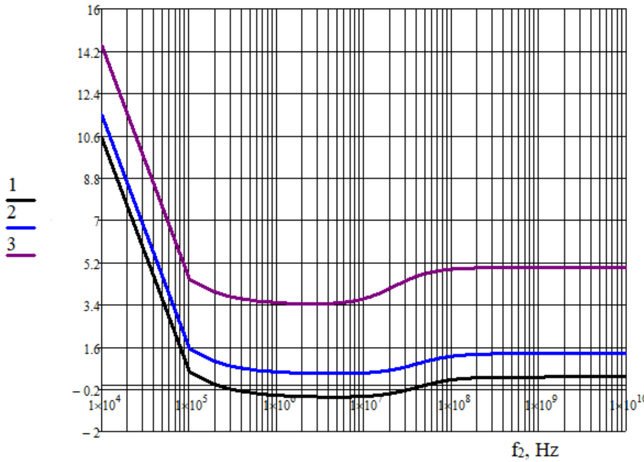

Fig. 1. Dependence $\mathrm{Re}(\dot{\varepsilon}_{\mathrm{R}}(f_2))$, $N_1 = 10^{15} m^{-3}$, $N_1 = 10^{17} m^{-3}$: 1 – for $\varepsilon_r = 3$; 2 – for $\varepsilon_r = 12$; 3 – for $\varepsilon_r = 25$.

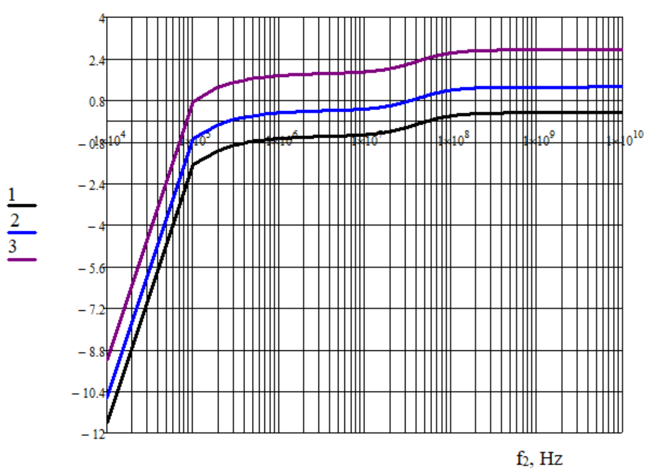

Fig. 2. Dependence $\mathrm{Re}(\dot{\varepsilon}_{\mathrm{L}}(f_2))$, $N_1 = 10^{15} m^{-3}$, $N_1 = 10^{17} m^{-3}$: 1 – for $\varepsilon_r = 3$; 2 – for $\varepsilon_r = 12$; 3 – for $\varepsilon_r = 25$.

The results of field measurements of the proposed method at Vostochno-Drozdovskoye oil deposit on the basis of the geological exploration device are shown in Figure 3.

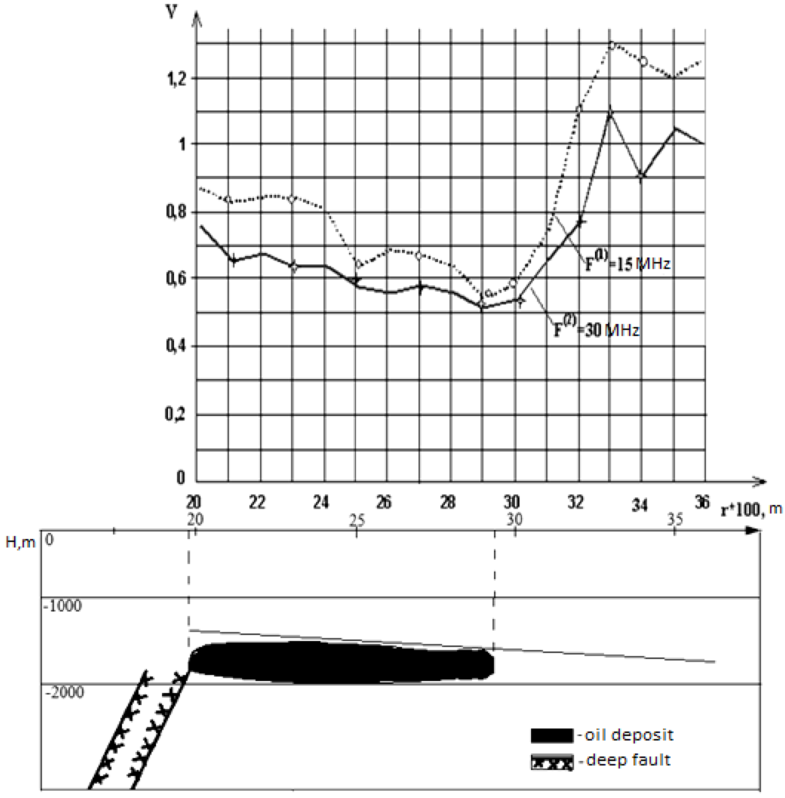

Fig. 3. Experimental field strength dependences.

The component for the left polarization of the wave (Figure 2) increases in the frequency range (20 – 600) MHz. In the higher frequency range of the signals used, positive values of this component are observed.

If the signal is considered as harmonic $e_2(t)$ with some frequency f_2, as well as electromagnetic wave as $e_1(t)$, the electromagnetic field can be represented as a superposition of two waves – a powerful surface electromagnetic wave with frequency f_1 and a low-power surface electromagnetic wave with frequency f_2.

Numerical studies of the tensor components (1) under the influence of the signal $e_1(t)$ in the frequency range $10^2 \ldots 10^{11}$ Hz for $\varepsilon_r = 2 \ldots 30$, $\sigma_r = 0{,}001$ S/m and $N_e = 10^{15} \ldots 10^{17}\,m^{-3}$ have shown that the maximum manifestation of the nonlinear effect of the interaction of the electromagnetic wave with the medium appears in the frequency range 10…30 MHz, when the frequency of the probing signal f_1 is close to or higher than the frequency of collisions between electrons and ions.

Due to the registration of field strength at combination frequency $F = f_1 \pm f_{1omp}$, where f_{1omp} is the reflected wave, which contains information about the natural variation of emission with frequency F as well as due to the use of nonlinear transformation of the probing signal and the signal of the natural emitting system in conditions of medium anisotropy, the reliability of determining the boundary and the accuracy of delineation of the deposit is increased.

By using frequencies $F^{(1)}$ = 15 MHz and $F^{(2)}$ = 30 MHz which were chosen because of maximum manifestation of the nonlinear interaction effect, the anomalous manifestation of the electromagnetic field at the boundaries of hydrocarbon deposits was obtained.

Figure 3 shows the results of experimental measurements expressed by the following dependence:

$$V = f(r) = \frac{A(r)}{E(r)}, \tag{2}$$

where $A(r)$ is total signal amplitude; $E(r)$ is the amplitude of natural emission of host rocks; r is the distance along the investigated profile.

The dashed and solid lines from the diagrams correspond to the values of the V ratio at frequencies $F^{(1)}$ and $F^{(2)}$.

4 Discussion

The boundary of the deposit is located at point № 29 as the value of V at this point has a minimum value. The effect of nonlinear interaction of signals is manifested in the decrease of amplitude A and leads to the reduction of V ratio to the values of 0.53 and 0.5. There is no effect outside the contour line, where the value of V is close to one, and deviation ΔV = ±0.2 at control points is $r \geq 32$.

The device realizing the method contains a generator, as which a standard ultra-high frequency generator with signal frequency f_1 = 8.5 GHz was used. The signal from the generator's output goes to the divider's input, which uses standard super-high-frequency connections, and from its output is fed to the two channels. This divides the power into two signals with equal amplitudes. One signal is fed to the antenna which irradiates the surface area at frequency f_1 and the second signal is fed to the mixer. The signal reflected from the surface is received by the antenna. Horn antennae with a 100×150 mm mouth and a standing wave coefficient of 1.5 are used, which are mounted at a fixed height from the Earth's surface or directly on it The mixer mixes two signals with frequencies f_1 and f_{1omp}. A and frequency F at the receiver input. The receiver is a superheterodyne receiver which is tuned to a discrete frequency.

This approach is associated with the use of research results, for which the hydrocarbon deposit is represented as a system built as a volume of reduced rocks and the surrounding geological space, forming a natural electromagnetic oscillating loop – an emitting system, the source of excitation of which is a natural alternating electric field.

The use of the proposed method of geoelectrical exploration of hydrocarbon deposits provides, in comparison with existing analogues, the following advantages: increased accuracy in determining the boundaries of hydrocarbon deposits; unambiguous determination of hydrocarbon deposits using the effect of nonlinear interaction of signals in conditions of anisotropy; selection of specific frequencies during exploration; significant reduction in the weight and dimensions of the geoelectrical exploration device; increased mobility of exploration devices; increased productivity; increased productivity of hydrocarbon accumulations; increased mobility of hydrocarbon accumulations; increased productivity of hydrocarbon accumulations.

Probing of hydrocarbon deposits under study based on dual-frequency signals using two types of polarization leads to increased productivity of exploration work and improved measurement techniques. Theoretical analysis of the characteristics of the anisotropic medium above the deposits and their experimental verification in the dual-frequency signal mode, as well as the establishment of patterns of physical and chemical processes in the anisotropic medium above hydrocarbons, leading to a change in the electrodynamic properties of these media, can be successfully combined with the geoelectric survey method (DNME), which allows obtaining data in shallow water, where other electromagnetic methods are difficult due to the energy of atmospheric waves (bottom logging or CSEM); with the GE method, showing encouraging results at great depths, in the transition zone and on land based on the visualization of anomalies in the response of the electric potential measured by the receiver as a result of geoelectric survey. Inversion of the recorded relaxation curve is performed to create a depth model. Differential-normalized methods of geoelectrospecting, rock characteristic and study of physical processes in the Earth's surface provide a set of broad-spectrum information for integrated analysis and complex interpretation of geophysical fields.

In this case, a radar portrait of the hydrocarbon deposit is formed, taking into account the properties of oil and hydrocarbons. The study of anisotropic properties of hydrocarbons can be significantly expanded by changing the distance between the transmitting and receiving devices, changing the routes of movement along a given geological area of the terrain, selecting several profiles for measurements, preferably passing in parallel and at fixed distances from each other. It is possible to perform work both on foot and in transport options. In this case, the results of modeling are taken into account using a wide range of variations in the electrodynamic characteristics of anisotropic media, using the climatic and seasonal features of a given research object. Feedback can also be used: based on the results of full-scale tests, amendments are made to the models of deposits, as a result, the models become adaptive. Such a correction is very productive and allows for multivariate analysis. The efficiency of search methods is determined by the characteristics of the signals used for probing. The result of these works is an increase in the accuracy of determining the boundaries of hydrocarbons. An important role is played by physical and geological features of reservoir rocks, which in turn are determined by mineralogical composition and particle size distribution of rocks, peculiarities of structural and textural structure of the skeleton in determining the combination of components of the dielectric permittivity of the medium over hydrocarbons. Doing geological and exploration studies it is necessary to solve a complex of technological, economic, organizational issues, to take as a basis the theoretical basis of oil and gas prospecting and exploration, existing methods of field geophysics, to take into account data in the field of gravity and magnetic exploration, to perform mathematical modelling of electric fields in the tasks of electrical exploration, to take into account the real geophysical environment. Taking measurements using two channels allows us to identify even small, low-contrast environments based on the fact that when locating survey points along the profile, the following situations are possible:

- If both points are outside the deposit, then with precise adjustment of the measuring equipment, the difference signal will be close to zero.
- If both points are above the deposit, then the difference signal may differ slightly from zero due to the anisotropic properties of the medium.
- If one measurement point is above the deposit, and the second is above the anisotropic medium, then the anomaly of the electromagnetic field will manifest itself significantly.

The surface impedance of the studied geological profile can be identified against the background of the environment, taking into account the left and right polarizations of electromagnetic waves. Additional information can be provided by the phase characteristics of dual-frequency signals. This is especially evident at high frequencies.If low values of the frequency component f_2 are applied it leads to an increase in the values of the real component for the right circular polarization and a decrease in the real component for the left circular polarization. The influence of variation of the amplitude ratio coefficients on the real components of the total and difference tensor components allows us to take into account the difference between water- and oil-saturated rocks for hydrocarbon deposits in terms of dielectric permittivity. For practical tasks in seasonal measurements it is necessary to take into account the change (decrease) of dielectric permittivity of rocks with increasing temperature, especially affecting the properties of water. This is explained by the disturbance of orientation of dipole molecules along the field direction with increasing temperature. The use of equipment for hydrocarbons searching, which has the ability to rearrange the amplitude range and recording of reflected signals, expands the information value of electrical exploration.

As a result of experimental measurements in registration of natural emission of hydrocarbon deposits at the Osipovichy gas storage facility it was established:

- The level of natural emission of hydrocarbon deposit above the dome is (5 –10) dBm higher than outside the dome.
- The natural emission level of hydrocarbon deposit exceeds the noise level of the off-land space by 25%.
- In the range (1 – 30) MHz there are components of the spectrum, where the increase of natural emission of hydrocarbon deposit is noted.

5 Conclusion

The analysis showed that:

- The distribution of the self-radiation of deposits across the frequency spectrum is uneven, it is determined by the power and depth of hydrocarbons.
- Anomalies of the electromagnetic field can reach (10 – 100) mV.
- The use of an auxiliary illumination transmitter allows identifying anomalies of the self-radiation of deposits.
- The accuracy of determining the boundaries increases due to this effect, since the signal of the self-radiation of deposits is added to the total signal.
- The experimental results confirm the effectiveness of this method and a high degree of identification of objects.

References

1. Yu. N. Stadnik, *Pearson's model in radio wave geophysics*, Geological Service of Russia 300 years: thesis. dokl. international. geophysis, October 2-6, 2000, St. Petersburg, Russia (2000)
2. Q. Sun, H. Tan, W. Wan, Q. Hu, Appl. Sci 14, 1560 (2024)
3. D.V. Gololobov, P.M. Cutlerov, Reports of BGUIR **4** (2003)
4. O.I. Abramov, Scientific World (2012)
5. V.G. Bondur, Scientific World (2012)
6. K.N. Petrov, Information processes 23, **1** (2023)
7. B. Arkoprovo and S.P. Shashi, West Bengal, India: Springer (2020)
8. A. Malemir, Geophysics 77, **5** (2012)