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DEVELOPMENT AND TESTING OF TOOLS FOR MODELING R&D WORKS IN GEOPHYSICAL INSTRUMENT-MAKING FOR OIL AND GAS WELL ELECTROMETRY

Introduction. R&D works are one of the first stages of any instrument-making. They may be simplified significantly through the effective use of modeling software. Mathematical modeling of electrometry helps avoiding expensive and time-consuming field or laboratory tests. Using such approach significantly increases the efficiency of designing new equipment.

Problem Statement. The vast majority of electrometry equipment used in Ukraine was developed in the middle of 20th century and is out-of-date. This equipment is not able to successfully solve many pressing problems of modern geophysical research. These problems include detection and determination of parameters for thin-layer, anisotropic reservoirs, residual oil saturation, abnormally high resistance etc. Fast and cheap development of new types of equipment is possible due to using mathematical modeling of many stages of R&D project. The successful use of mathematical modeling of electrometry requires not only the development and implementation of numerical methods to solve relevant direct problems, but also thorough testing before the implementation.

Purpose. The purpose of this research is the development and implementation of software and the testing of software and methodology for modeling R&D works related to oil and gas wells geophysical implementation.

Materials and Methods. Mathematical modeling of the problems related to electrometry of oil and gas wells.

Results. The developed software allows completing a number of assignments with the minimized time inputs. For example, user may calculate the ranges of measured values and study such parameters of the probe as vertical resolution and depth of survey for given geometry of the probe, initial conditions (supply parameters), and well conditions. In addition, the software allows setting the optimal value of any parameter of the probe to reduce the determination error of any geoelectric parameter of the selected formation, with the use of the developed minimization algorithm.

Conclusions. The software with methodological framework for modeling R&D works related to geophysical instrumentation for oil and gas wells electrometry has been developed, successfully tested, implemented and been

ready for the further introduction into production process. Such software may be effectively used for the creation of software for quantitative interpretation of electrometry data with the use of electrical survey and low-frequency induction survey methods.

K e y w o r d s : electrometry of oil and gas wells, electrical survey, low-frequency induction survey, software, mathematical modeling, research and development, and geophysical instrumentation.

Developing efficient use of Ukraine's mineral resource base is among the strategic tasks today [1]. Geophysical survey of wells, which is not possible without prior development of geophysical instrument-making is its important component. One of the first stages of any instrument-making is research and development (R&D) works that may be greatly simplified through the effective use of modeling software. Such modeling allows avoiding costly and time-consuming field and laboratory tests, which significantly increases the efficiency of the entire R&D unit. This research deals with the development and creation of software and methodological framework for R&D of geophysical instrument-making with the use of mathematical modeling tools (know-how) that have been already designed by the Institute of Telecommunications and Global Information Space of the NAS of Ukraine. The research deliverable is software and methodological framework developed and implemented.

The object of this research is the development of electrometry equipment for oil and gas wells with the most optimal characteristics for given well conditions, primarily, the conditions of the oil and gas wells of the Dnieper-Donetsk basin (DDB). In addition, such equipment should provide reliable initial data for solving the inverse problem (quantitative interpretation problem), because the solution of the inverse problem enables, based on the results of complex interpretation, more accurate answer to the question, where is the valuable fluid and how much it is there [2]. Therefore, the priority is to create hardware and methodological complexes, the design of which guarantees the possibility of the most accurate solution of the inverse problem.

Thus, the development of hardware and methodical complex becomes an iterative task: the designed equipment shall take into account the peculiarities of the algorithm for solving the inverse problem, and the algorithm for solving the inverse problem shall to take into consideration the design, engineering, and physical characteristics of the equipment. In this research, only electrometry is considered; other methods are not discussed, although they play a significant role in the interpretation of GSW data [3—5].

Electrometry equipment

Two physical principles of the electrometric penetration study of layers have been widely used: conventional electrical survey (CES) and low-frequency induction survey (LFIS). We do not consider the high-frequency induction survey (HFIS) method [6], because the current problems that are inherent in the conditions of DDB are solved with the help of CES and LFIS [7].

CES is used in wells that are filled with conductive drilling fluid (the resistivity is less than $0.5 \, \text{Ohm} \cdot \text{m}$), or weakly conductive solution (the fluid resistivity is $0.5—5 \, \text{Ohm} \cdot \text{m}$). The induction survey is used in wells filled with low-conductive or nonconductive fluid (the resistivity is greater than $5 \, \text{Ohm} \cdot \text{m}$). This division is quite conditional, but it is used in the domestic industry for geodetic survey of wells (GSW).

All the three mentioned types of wells (with conductive, low-conductive, and nonconductive drilling fluid) are inherent in the conditions of DDB, so the task of creating new electrometry equipment becomes the task of independent development of two different complexes for CES and LFIS.

The equipment of basic electrometry methods, which has been practically used in Ukraine, was developed in the mid-20th century and is obsolete. Such equipment consists of the three types:
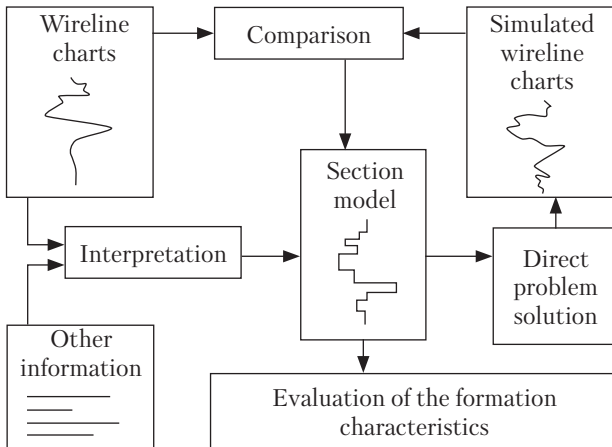
Fig. 1. Flowchart of the inverse problem solution

the equipment for multi-probe electrical survey (the MPES equipment), which is a set of potential and gradient probes that reach different depths, but have a low spatial resolution; the equipment consisting of one focused probe (the ES equipment); and the equipment consisting of one focused induction probe (the IP equipment).

Only MPES and ES equipment is used in the wells with a conductive fluid; MPES, ES, and IS equipment may be used for the wells with a low-conductive fluid; IS equipment and recently designed four-prove induction equipment are used in the wells with a nonconductive fluid [8]. The software and methodological complex for data interpretation of the latter has significantly expanded the range of tasks that may be successfully addressed by means of multi-probe induction survey [10, 11].

The use of the integrated MPES+ES+IS hardware has insurmountable disadvantages: in the wells filled with a nonconductive drilling fluid, there is only one IS measurement that does not allow establishing changes in the conductivity along the formation; in the wells filled with a conductive fluid we have only one measurement with high-resolution ES, and the change in conductivity along the formation is recorded with a low spatial resolution (it is impossible to establish the change in conductivity along low-capacity (thin) strata); in the wells with a low- conductive fluid,

where both methods (ES and IS) may be used, there are only two high-resolution measurements that are still insufficient to determine the three required parameters of thin strata of thin-stratum formation.

Therefore, we need to design new electrometry equipment that is capable of addressing present-day problems in the conditions typical for DDB.

Means of mathematical modeling for R&D works

There have been many designed and already practiced methods for modeling electrometry: the use of laboratory integrators, the finite-difference methods, the finite element methods, and so on. Such modeling is called the solution of a direct problem, which requires the use of some implemented method for obtaining a value that corresponds to a given accuracy of the value measured by a specific probe of a specific physical principle of measurement at a specific point of wellbore. The solution of direct problem is the main tool for modeling R&D works related to geophysical instrument-making for electrometry of oil and gas wells.

As the practice has shown, the most effective is the use of such methods of solving the direct problem, which may be used in the iterative process of solving the inverse problem (modern methods of solving the inverse problem are iterative processes [2], see Fig. 1) that at each iteration step requires solving the direct problem. That is why to achieve this goal we have decided to develop our own software tools for solving direct problems of ES and IS. We have chosen the method of integrated currents, the advanced Dole method that allows taking into account the interaction of currents in the medium, for ES [11].

Considering the effectiveness of algorithms for solving direct problems and methods for software implementation cannot be completed without the most important step, testing of reliability/robustness of the results provided by the developed and implemented algorithms.

In other words, it is not enough to get a way of solving a direct problem, which gives certain re-

sults depending on changing boundary conditions. In order to say confidently that we have a way (and its software implementation) to solve this direct problem, we shall make sure that the chosen method is correct and all the results are true (within the margin of error).

Testing of the software for mathematical modeling

Let us consider first the problems related to ES.

The first step in testing is to study the potential field that is calculated in the course of solving a direct problem.

Fig. 2 shows the spatial distribution of electric field potential for the case of an unfocused probe (point electrode *A* and inverted electrode *B* located on the conductive cable braiding). Having analyzed this distribution qualitatively and quantitatively, we conclude that the boundary conditions are set correctly (even visually, long conductive braiding of the logging cable is well observed); there are no extremums within the solution domain (the result corresponds to the condition of monotonicity for harmonic functions); at the outer boundaries of the area, the potential derivative goes to zero.

The same analysis has been repeated for the boundary conditions corresponding to the focused probe for electrical survey (see Fig. 3).

The second stage is to check the correspondence of the potential around the well axis, since in cylindrical coordinate system (in the case of axial symmetry, it is logically to solve such problems in cylindrical coordinate system) the Laplace equation:

$$\frac{1}{r}\frac{\delta}{\delta r}\left(r\frac{\delta U}{\delta r^2}\right)+\frac{\delta^2 U}{\delta r^2}+\frac{1}{r^2}\frac{\delta^2 U}{\delta\varphi^2}=0, \qquad (1)$$

at $r = 0$ has irregularity $1/0$.

Having multiplied equation (1) by r^2:

$$r\frac{\delta}{\delta r}\left(r\frac{\delta U}{\delta r}\right)+r^2\frac{\delta^2 U}{\delta r^2}+\frac{\delta^2 U}{\delta\varphi^2}=0, \qquad (2)$$

at $r = 0$ we obtain $\frac{\delta^2 U}{\delta\varphi^2}=0$, which is not an informative condition.
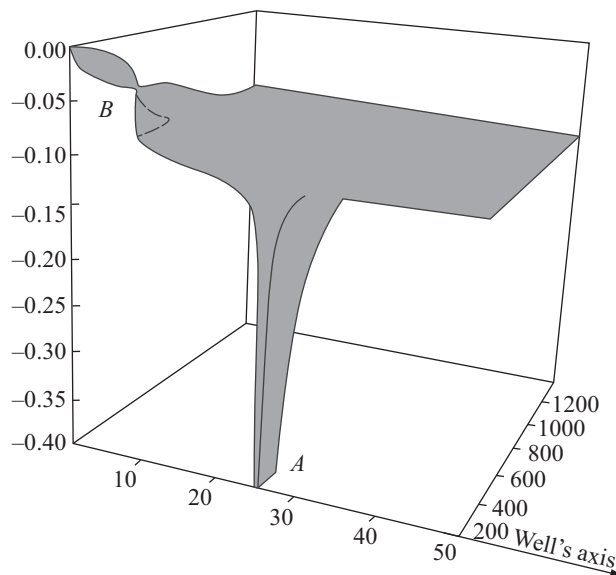

Fig. 2. Distribution of electric field p;otential in the case of unfocused probe (point electrode *A* and inverse electrode *B* located on conductive braiding of the cable)
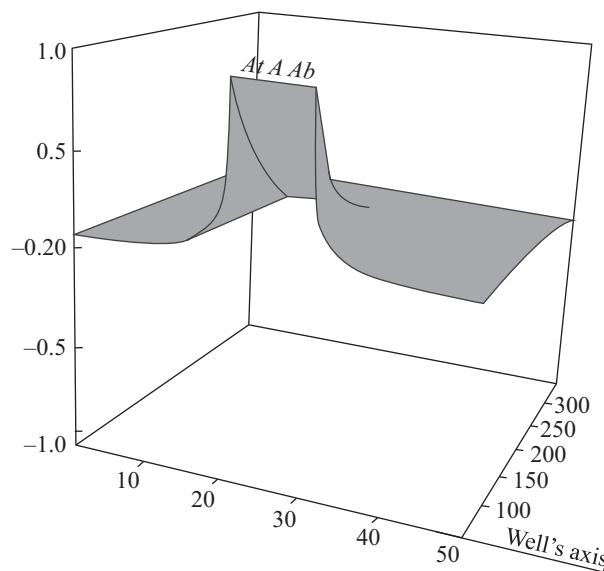

Fig. 3. Distribution of electric field potential in the case of focused probe for CES in the vicinity of electrodes having the same potential *A, Ab, At*

Usually, this irregularity is eliminated by means of boundary transition $r \to 0$ (see, for example, [12]. However, the direct use (1) or (2) for the assignments with unfocused probes, where point electrodes are located on the well axis, is impossible. Similarly, it is impossible to directly use

these probes for numerical calculations of the real values of the coefficients, under the same assumption. These numerical calculations are the next stage of testing, because the results may always be compared with the those calculated in [11]:

$$K = 4\pi \left(\frac{\overline{MA} - \overline{BM}}{\overline{MA} \cdot \overline{BM}} - \frac{\overline{NA} - \overline{NB}}{\overline{NB} \cdot \overline{NA}} \right)^{-1}.$$

A similar problem arises in connection with IS, if we consider the equation for the vector potential in cylindrical coordinate system.

The testing for error in the formation of the equations of the discrete model has been made by summing the currents crossing the shell that contains inside one or more electrodes with known current.

For the IS assignments, the test starts with qualitative and quantitative analysis of the dependence of the skin effect magnitude in homogeneous medium on the specific conductivity of this medium or frequency, in comparison with analytical formulas [13]:

$$\varepsilon_R = i\varepsilon_0 e^{-p} [(1 + p)\sin p - p\cos p],$$
$$\varepsilon_{Im} = \varepsilon_0 e^{-p} [(1 + p)\cos p + p\sin p],$$

where $p = L\sqrt{\frac{\sigma\mu\omega}{2}}$, $\varepsilon_0 = i\frac{\omega\mu M}{2\pi L^3}$, M is the dipole moment of the generator coil, ω is the excitation frequency, and μ is magnetic permeability.

A very important criterion for the correctness of the choice of algorithm parameters is the sensitivity of the results to variations in the already selected parameters of the discrete model. The study of such sensitivity is laborious and time-consuming, but necessary for testing.

For example, for the finite difference method, if we half the grid steps and the result changes by 1%, this indicated that at least at this point in our method most likely there is no error. Conversely, if the result changes significantly with a slight variation in the parameters of the discrete model, this means, we are still far from the correct result.

Such tests have been made for more complex models of the medium.

This is necessary because, eventually, one of the tasks of the numerical solution of direct prob-

lems may be to determine the range of sustainable operation of a particular equipment or to determine the limits of its sensitivity to a particular parameter of the model medium. Solving this problem in the analysis of the results is important to understand what we are dealing with, if there is a discrepancy between the obtained and the expected results: either the actual achievement of the operating range of the equipment or the error of the chosen method for solving the direct problem.

All these tests of the developed software have been made. Based on them, it has been concluded that for the selected parameters of the discrete model, the problem is solved with an error that is less than the predetermined one.

An informative test of the software is the comparison of its results with the results obtained by other software.

Various commercial software packages, such as *FemLab* (University of Florida), have been used for this comparison.

It should be noted that when using such packages, one should be very careful, because, for example, *FemLab* when trying to solve the direct ES problem for point electrodes located on the well axis in cylindrical coordinate system may give a result whose error is not immediately apparent. However, with the right use of commercial programs, the benefits of testing our own programs by comparison are hard to overestimate.

Figure 4 shows wireline charts of the probes of four-probe induction survey equipment for a formation pack (which contains in different sequences models of formations corresponding to water-bearing, net oil pay, gassy, clay, and compacted formations) obtained by the method of solving the direct IS problem (marked as "Software 1") and with the use of *FemLab* (marked as "*FemLab*"). The model of each formation is three-layered (well + zone of penetration of drilling mud filtrate (or "the zone") + part of the formation unaffected by drilling mud (or "the formation")).

Another form of testing is to compare the results with those obtained by the programs other
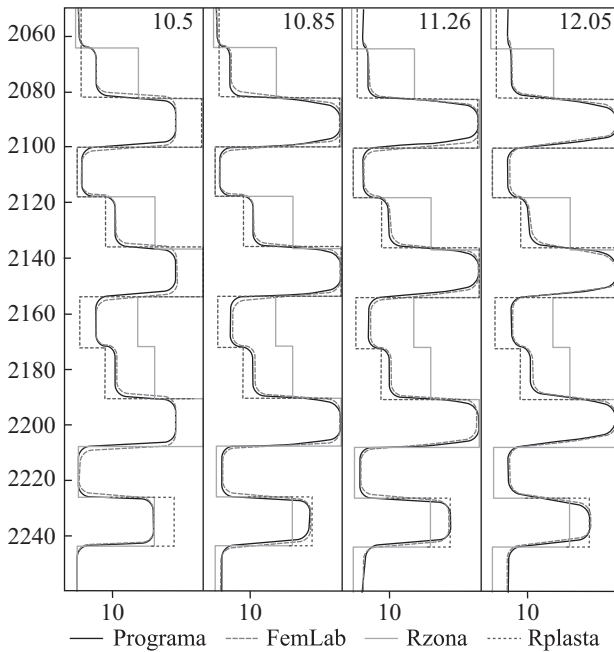
Fig. 4. Example of comparison of the results of solving the IS direct problem with the use of different software (R_{zone} is resistivity of the zone, $R_{formation}$ is resistivity of formation)

Fig. 5. Example of comparison of solutions to direct 2D problem obtained with the use of software developed by different authors, for the section containing three-layer formations (Resistivity of drilling mud is 2 Ohm·m; well radius is 0.1 m)

Fig. 6. Example of comparison of solutions to direct 2D problem obtained with the use of software developed and implemented by different authors, for the section containing three-layer formations (Resistivity of drilling mud is 2 Ohm·m; well radius is 0.1 m)

than the commercial ones, i.e. with the programs that have been implemented by other researchers in the field of electrometry, for the same models and the same probes.

Such a comparison has been made in Novosibirsk (at the Trofimuk Institute of Oil and Gas Geology and Geophysics, Siberian Branch of the RAS), for the software for solving a two-dimensional direct problem of CES, upon the agreement on formats for setting the boundary conditions and obtaining the results.

A series of calculations with the use of the software developed by the Novosibirsk colleagues has been made (Figs. 5, 6) ("Software 1") and our software ("Software 2") and the results have been compared.

When discussing the results of the comparison, we have found that some differences may arise due to different representations in the simulation of the inverse current electrode (in the actual software it is presented as a conductive braiding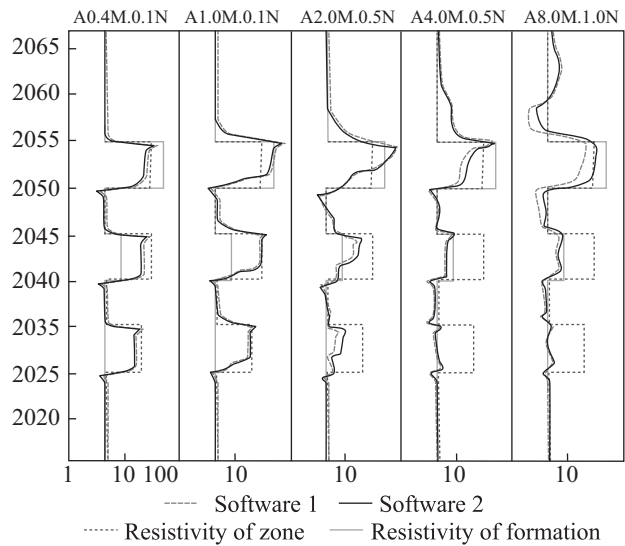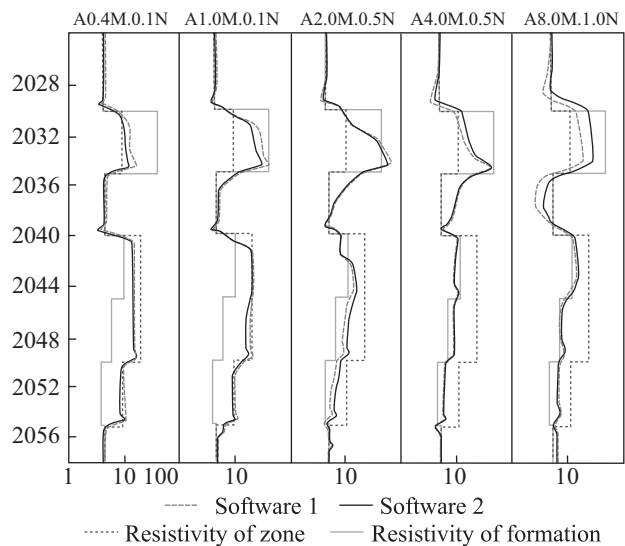 of the cable at a finite distance from the direct current electrode instead of as a point electrode). Other discrepancies are the result of the approximate nature of any numerical calculation and in this case objectively reflect its actual error.

The main test of the correctness/robustness of the algorithm for solving the direct problem is to assess its validity for solving the inverse problem that uses it (see Fig. 1). At least, the evaluation of the results of the inverse problem in comparison with other data of geological interpretation and lithological dissection allows us to immediately identify obvious errors in the implementation of the solution to the direct problem.

In addition to the described use in R&D works and the use of software and methodological tools for solving the inverse problem [14, 15], the created modeling tools have allowed studying the relationship between the measurement error and the error of solving the inverse problem [16], as well as the areas of equivalent solutions of the inverse problem [17].

The approaches that have been used in this research are applicable not only for solving problems of electrometry modeling [18—21].

By means of modeling, the developed software enables with minimum time inputs:

1. Calculating the ranges of measured values and studying the characteristics of the probe (vertical resolution, depth of research, etc.), for a given geometry of the probe, given initial conditions (supply parameters) and well conditions

2. Setting the optimal value of any probe parameter to reduce the error of setting any geoelectric parameter of the selected formation with the use of the created minimization algorithm.

The developed software has been successfully implemented in the production process at Prydniprovska Mining and Chemical Corporation LLC in a way that is not limited to the three-layer section model, as it allows modeling electrometry in formations of any spatial distribution. Such software may be effectively used in the creation of software for the quantitative interpretation of electrometry data of EC and IS methods.

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РОЗРОБКА ТА ТЕСТУВАННЯ ЗАСОБІВ МОДЕЛЮВАННЯ
НАУКОВО-ДОСЛІДНОЇ ТА ДОСЛІДНО-КОНСТРУКТОРСЬКОЇ
РОБІТ ГЕОФІЗИЧНОГО ПРИЛАДОБУДУВАННЯ
ЕЛЕКТРОМЕТРІЇ НАФТОГАЗОВИХ СВЕРДЛОВИН

Вступ. Одним з перших етапів будь-якого приладобудування є науково-дослідні (НД) та дослідно-конструкторські роботи (ДКР). Математичне моделювання дозволяє уникнути високовартісних та тривалих у часі натурних чи лабораторних випробувань. Це підвищує ефективність розробки нової апаратури.

Проблематика. Переважна більшість використовуваної в Україні апаратури електрометрії є морально застарілою. Розробка нових типів апаратури можлива з використанням математичного моделювання низки етапів НД та ДКР. Математичне моделювання електрометрії вимагає не тільки розробки та реалізації числових методів розв'язання відповідних прямих задач, а й ретельного тестування їх перед впровадженням.

Мета. Розробка, програмна реалізація та тестування програмно-методичного забезпечення моделювання НД та ДКР геофізичного приладобудування електрометрії нафтогазових свердловин.

Матеріали й методи. Застосовано математичне моделювання задач електрометрії нафтогазових свердловин.

Результати. Розроблене програмне забезпечення дозволило із мінімальними затратами ресурсів часу за допомогою моделювання для заданих геометрії зондової частини, початкових умов (параметри живлення) та свердловинних умов розраховувати діапазони вимірюваних величин та досліджувати характеристики зонду (вертикальну роздільну здатність, глибину дослідження тощо); за допомогою створеного алгоритму мінімізації встановлювати оптимальне значення будь-якого параметра зонду для зменшення похибки визначення будь-якого геоелектричного параметра обраного пласта.

Висновки. Запропоновано розроблене та реалізоване програмно-методичне забезпечення моделювання НД та ДКР геофізичного приладобудування електрометрії нафтогазових свердловин, що пройшло успішне тестування та готове до подальшого впровадження у виробничий процес. Його можна ефективно використовувати при створенні відповідного програмного забезпечення кількісної інтерпретації даних електрометрії методами електричного та низькочастотного індукційного каротажу.

Ключові слова: електрометрія нафтогазових свердловин, електричний каротаж, низькочастотний індукційний каротаж, програмне забезпечення, математичне моделювання, науково-дослідні та дослідно-конструкторські роботи, геофізичне приладобудування.