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https://orcid.org/0000-0002-6000-6477
https://orcid.org/0000-0002-0964-3008
https://orcid.org/0000-0002-2224-6453
https://orcid.org/0000-0002-3334-645X
https://orcid.org/0009-0007-4325-1677

LOCALIZATION OF NMR SOURCES USING TDOA AND AMPLITUDE ANALYSIS METHODS


Z.B. IMANSAKIPOVA,
PhD, senior lecturer,
z.imansakipova@satbayev.university

SH.K. AITKAZINOVA,
PhD, Associate professor,
sh.aitkazinova@satbayev.university


M.S. BUKENOVA,
MSc, senior lecturer,
m.bukenova@satbayev.university

N.B. IMANSAKIPOVA,
PhD, Associate professor,
nurlanaimansakipova@mail.ru

M.S. KURBANBEKOV, doctoral student, researcher, *mkurbanbekov@kmge.kz*

SATBAYEV UNIVERSITY
Republic of Kazakhstan, 050013, Almaty, Satbayev str. 22

The paper proposes a method for spatial localization of NMR signal sources during downhole studies of oil reservoirs in the Earth's natural magnetic field. The method is based on the combined use of electromagnetic wave arrival time differences (TDOA) and signal intensity measurements recorded by a system of four receivers placed on the day surface.

It is shown that the time delay method provides high geometric accuracy, but is sensitive to the uncertainty of the wave velocity propagation in an inhomogeneous medium, while the amplitude method is more resistant to velocity variations, but is subject to noise and errors in the attenuation coefficient. A weighted average combination of the results of the two methods is proposed.

The simulation results showed a decrease in the error in determining the coordinates of the source from 3–5 m (TDOA) and 8–12 m (amplitude method) to ~2 m with a combined approach. In addition, it was found that the use of fixed time delays allows for coherent signal accumulation, increasing the signal-to-noise ratio.

The proposed approach can be used to create areal monitoring systems for oil fields based on off-hole NMR studies.

KEYWORDS: *NMR signals, TDOA, amplitude method, localization, attenuation coefficient, signal-to-noise.*

ЛОКАЛИЗАЦИЯ ИСТОЧНИКОВ NMR-СИГНАЛОВ МЕТОДАМИ TDOA И АМПЛИТУДНОГО АНАЛИЗА

З.Б. ИМАНСАКИПОВА, PhD, старший преподаватель, *z.imansakipova@satbayev.university*
Ш.К. АЙТКАЗИНОВА, PhD, ассоциированный профессор, *sh.aitkazinova@satbayev.university*
М.С. БУКЕНОВА, магистр, старший преподаватель, *m.bukenova@satbayev.university*
Н.Б.ИМАНСАКИПОВА, PhD, ассоциированный профессор, *nurlanaimansakipova@mail.ru*
М.С. КУРБАНБЕКОВ, докторант, исследователь, *mkurbanbekov@kmge.kz*

SATBAYEV UNIVERSITY
Республика Казахстан, 050013, Алматы, ул. Сатпаева, 22

В работе предложен метод пространственной локализации источников NMR-сигналов при внескважинных исследованиях нефтяных коллекторов в естественном магнитном поле Земли. Метод основан на совместном использовании разностей времён прихода электромагнитной волны (TDOA) и измерений интенсивности сигнала, регистрируемых системой из четырёх приёмников, размещённых на дневной поверхности.

Показано, что метод временных задержек обеспечивает высокую геометрическую точность, но чувствителен к неопределённости скорости распространения волны в неоднородной среде, тогда как амплитудный метод более устойчив к скоростным вариациям, но подвержен шумам и ошибкам в коэффициенте затухания. Предложено средневзвешенное объединение результатов двух методов.

Результаты моделирования показали снижение погрешности определения координат источника с 3–5 м (TDOA) и 8–12 м (амплитудный метод) до ~2 м при комбинированном подходе. Дополнительно установлено, что использование фиксированных временных задержек позволяет выполнять когерентное накопление сигналов, повышая отношение сигнал/шум.

Предложенный подход может быть использован для создания систем площадного мониторинга нефтяных месторождений на основе внескважинных NMR-исследований.

КЛЮЧЕВЫЕ СЛОВА: *NMR-сигналы, TDOA, амплитудный метод, локализация, коэффициент затухания, сигнал/шум.*

TDOA ЖӘНЕ АМПЛИТУДАЛЫҚ ТАЛДАУ ӘДІСТЕРІН ҚОЛДАНУ АРҚЫЛЫ NMR КӨЗДЕРІН ЛОКАЛИЗАЦИЯЛАУ

З.Б. ИМАНСАҚЫПОВА, PhD, аға оқытушы, *z.imansakipova@satbayev.university*
Ш.К. АЙТКАЗИНОВА, PhD, қауымдастырылған профессор, *sh.aitkazinova@satbayev.university*
М.С. БӨКЕНОВА, магистр, аға оқытушы, *m.bukenova@satbayev.university*
Н.Б. ИМАНСАҚЫПОВА, PhD, қауымдастырылған профессор, *nurlanaimansakipova@mail.ru*
М.С. ҚҰРБАНБЕКОВ, докторант, зерттеуші, *mkurbanbekov@kmge.kz*

SATBAYEV UNIVERSITY,
Қазақстан Республикасы, 050013, Алматы қ., Сәтбаев к., 22

Бұл жұмыста Жердің табиғи магнит өрісіндегі мұнай қабатын ұңғымадан тыс зерттеулер кезінде NMR сигнал көздерін кеңістікте локализациялау әдісі ұсынылады. Әдіс жер бетінде орналасқан төрт қабылдағыш жүйесімен жазылған электромагниттік толқынның келу уақыты (TDOA) және сигнал қарқындылығын өлшеуді біріктіріп қолдануға негізделген.

Уақытты кідірту әдісі жоғары геометриялық дәлдікті қамтамасыз етеді, бірақ біртекті емес ортада толқынның таралу жылдамдығының белгісіздігіне сезімтал, ал амплитудалық әдіс жылдамдықтың өзгеруіне сенімдірек, бірақ әлсіреу коэффициентіндегі шу мен қателерге сезімтал. Екі әдістің нәтижелерінің орташа өлшенген комбинациясы ұсынылады.

Модельдеу нәтижелері біріктірілген тәсілді пайдалана отырып, тарату көзін орналастыру қателігінің 3–5 м (TDOA) және 8–12 м (амплитудалық әдіс) ~ 2 м дейін азайғанын көрсетті. Сондай-ақ, белгіленген уақыт кідірістерін пайдалану сигналдың шуылға қатынасын жақсарта отырып, когерентті сигнал жинақтауға мүмкіндік беретіні анықталды.

Ұсынылған тәсіл ұңғыма сыртындағы NMR зерттеулерінің негізінде мұнай кен орындарының аумақтық мониторингі жүйелерін құру үшін пайдаланылуы мүмкін.

ТҮЙІН СӨЗДЕР: *NMR сигналдары, TDOA, амплитудалық әдіс, локализация, әлсіреу коэффициенті, сигнал/шу.*

Introduction. In the petroleum industry, nuclear magnetic resonance technology is widely used in the laboratory and for borehole logging, which provides important information about the petrophysical properties of reservoirs such as porosity, permeability, wettability, irreducible water saturation and irreducible oil saturation. Downhole and laboratory applications of NMR measurements are used in both conventional and non-conventional reservoir systems to quantify critical parameters such as pore size distribution, porosity, and permeability. The use of NMR also provides a better understanding of the interaction between reservoir fluids and the properties of the host rocks.

At the same time, oil production, the use of enhanced oil recovery (EOR) methods and other geological and technical measures (GTM) cause changes in the state, structure and properties of reservoirs throughout the field of varying intensity. In this regard, there is an urgent need to organize monitoring covering the entire field. In this direction, the use of NMR studies is limited by the need to maintain a stable external magnetic field in the places where they are performed. One of the solutions to this problem is the possibility of using the Earth's magnetic field as an external one. Despite different approaches to this issue, no effective solution has been presented. For example, it is proposed to use test plates on which the NMR spectra of the material under study are recorded, serving as resonators. For a comparative analysis of the spectrum of a space image of the territory in the infrared range. The disadvantages include the ambiguity of the identification of test and full-scale spectra due to differences in the strength of the Earth's magnetic field at the time of their acquisition. In addition, the spectrum of the satellite image within the pixel is a set of NMR spectra of local oil reservoirs that are in different states and are not localized.

One of the promising areas of NMR research in conditions of weak and pulsating magnetic field of the Earth is the method based on simultaneous registration of the NMR signal and the current value of the magnetic field strength using a precision magnetometer. Successful implementation of the method is currently limited by the problem of unambiguous determination of the source of the NMR signal. When studying the reservoir in the Earth's natural magnetic field, covering the entire field, the position of the NMR signal source turns out to be spatially uncertain. This predetermines the need for thelocalization of signal sources for NMR identification.

Materials and methods

It follows from the wave theory that the localization of the radiation emission source does not depend on the physical nature of the formation of waves, but is determined by their parameters and the magnitudes of the influence of the medium in which they propagate. Therefore, the approaches to determining the coordinates of the signal source developed by seismoacoustic methods [1], which have found wide and successful application in geophysics, seismology and materials science, are of exceptional interest for the development of new and improvement of known methods for use in the localization of NMR sources – signals.

Conventionally, the methods of localization of the radiation emission source can be divided as follows.

1. The Time Difference of Arrival (TDOA) method is based on the fact that the front of an electromagnetic wave reaches spatially separated receivers at different points in time. For NMR signals: the wavelength is significantly less than the distance to the source → geometric optics approximation is performed; the signal propagates quasi-spherically; Arrival times can be measured with high accuracy when synchronization is available. In a multilayer geological environment, the speed of propagation of an electromagnetic wave is determined by the effective dielectric constant and electrical conductivity of rocks. This leads to: refraction at the boundaries of layers, changes in the effective velocity, possible anisotropy of propagation. Thus, TDOA is applicable, but its accuracy is limited by the uncertainty of the velocity model of the medium.

The coordinates of the source are determined by solving a system of equations that relate the delay times and the speed of wave propagation in the medium. These methods are widely used in seismology and microseismic monitoring, as well as in electromagnetic reconnaissance and radio navigation.

2. Amplitude and energy methods. Another group of methods uses the spatial distribution of amplitudes or intensities of signals, taking into account the geometric divergence and attenuation of waves in the medium. Such methods are used in the localiza-

tion of sources of acoustic emission and microseismic events. Their accuracy essentially depends on knowledge of the attenuation coefficients and homogeneity of the medium.

3. The modal acoustic emission method is based on measuring the arrival time of longitudinal and flexural waves with a single sensor. If their respective propagation velocity is known, distance can be measured [2,3]. However, the difficulty lies in implementing the separation of longitudinal and flexural waves in practice, since the distances are small and the waves overlap.

4. The triangulation method is based on the precise measurement of the arrival time and velocity of the wave. There are varieties of the method based on knowledge and without knowledge of the speed of wave propagation. Various computational procedures have been developed to calculate the velocity of wave propagation.

5. Beamforming is a signal processing method that uses a group of sound receivers to determine the direction of arrival of a wave. Since beamforming compares waveforms, all sensors in the array must have the same amplitude and phase responses. Antennas should have a small aperture.

6. The Time reversal and artificial neural network method is suitable for localizing the source of acoustic emission in an anisotropic medium and the algorithm does not require knowledge of the wave propagation velocity. Since time reversal measures the phase of signals, identical conditions are required for forward and reverse propagation. But the Artificial neural network method requires a lot of data for deep learning.

7. The Multiple sources localization method solves the problems of distinguishing between different sources of signals, which is necessary for the practical implementation of many methods.

8. Hybrid methods. To increase the stability of solutions in a complex geological structure, combined methods are used that combine time and amplitude parameters of signals. Similar approaches are used in hydraulic fracturing monitoring systems and in the localization of electromagnetic sources in inhomogeneous media.

A lot of research is devoted to determining the localization of acoustic emission signals [4-7].

For instance, the article [8] reviews methods of localizing acoustic emission sources in various dimensions. The main methods of localization of the source of acoustic emission in a two-dimensional dimension are considered, such as triangulation, beam forming, strain rosette technique, modal AE, artificial neural networks, optimization and time reversal technique, methods of localization in isotropic and anisotropic structures, as well as methods of localization in complex structures in a three-dimensional dimension. As one of the main directions for future research, the authors note the need to conduct research on the localization of the source in three-dimensional structures.

Meanwhile the article [9] presents an overview of traditional methods of localization of acoustic sources based on signal processing, as well as modern methods based on the use of deep neural networks. The advantages and disadvantages of the above methods are analyzed and considered. While some traditional methods can adapt to the observed signals, they all depend on accepted assumptions and assumptions about the nature of the medium, the properties of the signals, and so on. However, this is also a major drawback of modern methods, as they are less generalizable and less versatile than traditional methods. The need for the development of new localization methods, as well as the integration of traditional and modern intellectual localization methods to combine the advantages of each of these groups of methods is substantiated.

The authors also conducted a comparative review of well-known methods for localizing acoustic emission sources in the article [10]. Well-known methods for localizing acoustic emission sources, such as modal acoustic emission, triangulation method, beamforming, time reversal and artificial neural network, multiple sources localization, were considered.

Acoustic emission source (AE) localization technology, pioneered in one-dimensional structures, has been extended to a wide range of applications in two-dimensional (2D) structures, including isotropic and anisotropic materials, which are currently the most widely studied and most advanced. With the development of AE source localization technology, more and more serious problems arise related to three-dimensional (3D) structures, which are mostly anisotropic and have complex propagation pathways.

The article [11] summarizes and discusses methods for localizing AE sources in various dimensions, as well as their applications, including the main methods for localizing 2DAESOURCE sources, such as the tetraangulation method, beamforming, stretching method, modal AE, artificial neural network, optimization and time-reversal method, as well as modern methods for localizing AE sources in different dimensions. isotropic and anisotropic structures using these methods. The latest achievements in the field of localization of sources in complex structures are considered.

In turn the paper [12] presents an overview of traditional methods for localizing acoustic sources based on signal processing, as well as modern methods based on the use of deep neural networks. The advantages and disadvantages of the above methods are analyzed and considered. While some traditional methods can adapt to the observed signals, they all depend on accepted assumptions and assumptions about the nature of the environment, the nature of the signals, and so on. However, this is also a major drawback of modern methods, as they are less generalizable and less versatile than traditional methods. The need for the development of new localization methods, as well as the integration of traditional and modern intellectual localization methods to combine the advantages of each of these groups of methods is substantiated.

Whereas in the article [13], the acoustic emission method is one of the effective methods of non-destructive testing of the stress-strain state of rocks. At the same time, the source of the signal is the rocks under study. Geoacoustic radiation signals are a combination of pulses of different amplitude, duration (about 30-100 ms) and fill rate (up to 10 kHz), with a steep edge and a smooth decay. The pulse repetition frequency varies from units per minute to several hundred per second, depending on the stress-strain state of the rocks. The article presents the results of an experiment to determine the distance to sources of high-frequency acoustic radiation generated in near-surface sedimentary rocks. Such signals were recorded using a distributed system installed in a natural reservoir, consisting of two combined receivers and one omnidirectional sound pressure receiver. The use of combined receivers makes it possible to reconstruct the spatio-temporal distribution of the vector of the oscillatory velocity of the particles of the medium in the wave using vector-phase methods and to determine the direction to the signal source. Localization of radiation sources was carried out in two ways: triangulation and by the difference in the time of arrival of signals from spaced receivers. The coordinates of more than 40 sources of acoustic radiation have been measured, and their spatial distribution has been constructed. The measurement error was less than 0.5 m.

Most of the alternative studies are devoted to the development and improvement of methods based on the measurement of the time difference of wave arrival (TDOA) In "blind" tuning conditions, when the initial signals are unknown, the localization task is difficult due to the problem of data matching [12]. That is, it is not known which of the TDOA measurements correspond to the same source. In this case, it is proposed to perform joint localization and association of data using an optimal transport scheme. The method is based on finding the optimal groupings of TDOA dimensions and comparing them with possible source locations. In the works [13], [14] the problem of determining the direction without reference using measurements of the difference in time of arrival of signals (TDOA) from several sources located at a large distance in three-dimensional space is considered. A systematic solution is proposed, including the construction of a coordinate system, to jointly evaluate source directions and sensor positions using low-rank matrix approximation. The article [15] notes that TDOA-based methods can achieve good positioning results if the acoustic wave velocity is known with great accuracy. However, in complex and variable environments, the acoustic wave velocity may contain a certain degree of uncertainty or even be unknown, which significantly limits the use of traditional methods based on pre-measured velocities.

Meanwhile the article [16] notes that the inhomogeneities of the medium limit the accuracy of source localization algorithms. To overcome these shortcomings, it was proposed to use in conjunction with algorithms for localization of acoustic emission sources with tomography based on the time of propagation.

Consequently in the paper [16] was proposed to use traditional TDOA and beamforming methods together to localize acoustic emission sources.

Thus, despite the large number of works aimed at solving the problem of localizing the source of wave emission, the most accessible and effective method is (TDOA). The main disadvantage of which is the expected degree of uncertainty, the value of the wave propagation velocity in an anisotropic medium.

In order to increase the stability and unambiguousness of finding the coordinates of the source in a complex geological structure, it is proposed to use a method that combines the temporal and amplitude parameters of the signal based on the following model.

Determination of the location of the NMR signal source is carried out by a system of four spatially separated receivers, at each receiver simultaneously with the delay time, the intensity of the received wave is measured, the coordinates of the receivers are established, the difference in the distances of each of the two receivers to the source is determined as the product of the wave velocity and the delay time, from the obtained equations a system of three equations with three is made unknown coordinates of the source of the electromagnetic wave signal, solve the system of equations, establish the coordinates of the source, for each receiver write down the equation of the dependence of the recorded wave intensity on the intensity of the wave in the source, the distance from the source to the receiver and the attenuation coefficient, from the obtained equations they make a system of three equations with three unknown coordinates of the source, solve the system of equations, establish the coordinates of the source, carry out a weighted average combination of the results obtained and obtain the final value of the coordinates of the radiation source. The combination of TDOA and amplitude analysis allows you to compensate for the limitations of each.

1. Determination of NMR source coordinates by signal reception delay time

Four receivers with predetermined coordinates are placed in space: $(x_i, y_i, z_i), i=1...4$ (*Fig.1*). Receivers R_1, R_2, R_3, R_4, located at a distance r_1, r_2, r_3, r_4, respectively from the source S, record the time of arrival of the electromagnetic signal t_1, t_2, t_3, t_4.

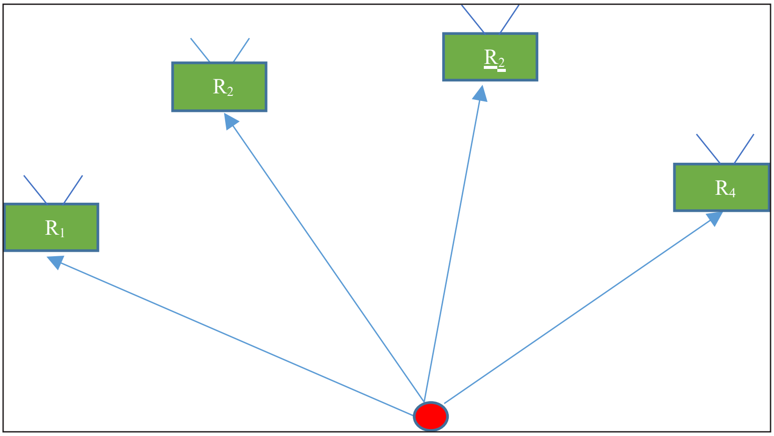

Figure 1 – **Diagram of the location of signal receivers relative to the source**

The time of emission of an electromagnetic wave by the source t_0, the time of arrival of the signal to each receiver: t_1, t_2, t_3, t_4. During the period of time between emission and reception, the wave travels the distance r_i from the source to the receiver at a speed n:

$$r_{I=C} \cdot (t_{1-t0}) \quad (1)$$

Receiver 1 is chosen as a reference. Calculate the difference in arrival times (delay time) for each receiver relative to the reference receiver:

$$\begin{gathered} \Delta t_{21} = t_2 - t_1 \\ \Delta t_{31} = t_3 - t_1 \\ \Delta t_{41} = t_4 - t_1 \end{gathered} \quad (2)$$

A system of three nonlinear equations with three unknown coordinates of the source x, y, z is formed from (1) and (2):

$$\begin{gathered} r2 - r1 = c\Delta\, t21 \\ r3 - r1 = c\Delta\, t31 \\ r4 - r1 = c\Delta\, t41, \end{gathered} \quad (3)$$

where
$$r_1=\sqrt{x-x_1)^2+(y-y_1)^2+(z-z_1)^2}$$
$$r_2=\sqrt{x-x_2)^2+(y-y_2)^2+(z-z_2)^2}$$
$$r_3=\sqrt{x-x_3)^2+(y-y_3)^2+(z-z_3)^2}$$
$$r_4=\sqrt{x-x_4)^2+(y-y_4)^2+(z-z_4)^2}$$

To solve nonlinear equations, a modified Newton–Raphson method is used using the Python programming language. The use of the Python library allows you to implement numerical methods and localization algorithms. Let's outline:

$$f_{i(x,y,z)} = \sqrt{x-x_i)^2+(y-y_i)^2+(z-z_i)^2} - \sqrt{x-x_1)^2+(y-y_1)^2+(z-z_1)^2} - c\Delta t_{i1} \quad (4)$$

Accordingly, the Jacobian system

for $i=2,3,4$:

$$\frac{\partial f_i}{\partial_x} = \frac{x-x_i}{r_i} - \frac{x-x_1}{r_1}$$
$$\frac{\partial f_i}{\partial_y} = \frac{y-y_i}{r_i} - \frac{y-y_1}{r_1} \quad (5)$$
$$\frac{\partial f_i}{\partial_z} = \frac{z-z_i}{r_i} - \frac{z-z_1}{r_1}$$

The iterative algorithm for the Newton-Raphson method will be:
on the k-th iteration:

$$q^{k+1} = q^k - (J^T J)^{-1} J^T F(q^k) \quad (6)$$

where $q = (x, y, z)^T$

$$F = \{f_i\} \text{ or } \{g_i\}$$

The conditions for stopping iterations are $\|q^{k+1} - q^k\| < \varepsilon$.

2. Determination of NMR source coordinates based on the intensity of the received signal

Since the distances from the acoustic emission source to the receiving sensors are quite large compared to the acoustic wave waves, the distances between the sensors are commensurate with the distances from them to the emission source, and the sources themselves are local, a spherical wave is formed in a solid medium.

The dependence of intensity for a spherical acoustic wave on distance is given by the equation:

$$I = \frac{I_0}{r^2} e^{-\Delta r} \quad (7)$$

where is the intensity of the acoustic emission source, I_0 Δ is the attenuation coefficient in the medium, r is the distance from the measuring point to the acoustic emission source.

The wave intensity at each receiver is:

$$I_1 = \frac{I_0}{r_1^2} e^{-\Delta r_1}$$
$$I_2 = \frac{I_0}{r_2^2} e^{-\Delta r_2} \qquad (8)$$
$$I_3 = \frac{I_0}{r_3^2} e^{-\Delta r_3}$$
$$I_4 = \frac{I_0}{r_4^2} e^{-\Delta r_4}$$

Let's calculate the intensity ratios:

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} e^{\Delta(r_2 - r_1)}$$
$$\frac{I_1}{I_3} = \frac{r_3^2}{r_1^2} e^{\Delta(r_3 - r_1)} \qquad (9)$$
$$\frac{I_1}{I_4} = \frac{r_4^2}{r_1^2} e^{\Delta(r_4 - r_1)}$$

Taking into account (3), (9) represents a system of three nonlinear equations with three unknown coordinates of the source *x, y, z.*

To solve this system by analogy with the system obtained from the delay times (3), a modified Newton–Raphson method with Jacobian is used:

$$\frac{\partial g_i}{\partial_x} = \left(\frac{2}{r_i} + \Delta\right)\frac{x - x_i}{r_i} - \left(\frac{2}{r_1} + \Delta\right)\frac{x - x_1}{r_1}, \qquad (10)$$

where $g_{i(x,y,z)} = 2In\frac{r_i}{r_1} + \Delta(r_i - r_1) - In\frac{I_1}{I_i}$, is obtained from the differentiation of the equation of the system (9).

Both methods estimate coordinates, differing in their approaches to the Signal Delay Time (TDOA) and signal intensity solutions.

TDOA has high geometry accuracy and is weakly dependent on transmitter power, but is sensitive to synchronization and does not perform well in anisotropic environments.

The intensity method differs in that it does not require exact synchronization, is easy to implement, but strongly depends on the attenuation of the medium (logarithmic error).

To improve the accuracy and unambiguousness of determining the coordinates of the source, a weighted average combination of the results of the two methods is proposed:

$$\vec{S} = \frac{w_1 S_{TDOA} + w_1 S_{инт}}{w_1 + w_2} \qquad (11)$$

where S, STDOA, SINT are the coordinates of the source, respectively, the defined combination of the results of the two methods, by the TDOA method, by the intensity methods, w_1, w_2 are weight coefficients determined by the accuracy of measurements by each of the methods.

To check the correctness of the tasks set and the developed algorithms for their solution, a simulation experiment was carried out with the following initial data (*Table 1*).

Table 1 – **Initial data for the simulation experiment**

Coordinates	$R_{1,}$ m	$R_{2,}$ m	$R_{3,}$ m	$R_{4,}$ m	$S_{,}$ m
x	0	10	0	0	300
y	0	0	10	0	400
z	0	0	0	10	200

The velocity of the electromagnetic wave is *c=2.0·10−8 m/s.* The real distances *are* $r_1=538.5$ *m,* $r_2=533.1$ *m,* $r_3=531.2$ *m,* and $r_4=534.9$ *m.* Determination of source coordinates based on the signal delay time.

Distance differences:

$$r_2-r_1=-5.4\ m$$
$$r_3-r_1=-7.3\ m$$
$$r_4-r_1=-3.6\ m$$

Measured time delays

$$\Delta t_{i1}=\frac{r_i-r_1}{c}$$
$$\Delta t_{21}=\frac{5.4}{2.0\cdot 10^{-8}}=2.70\cdot 10^{-8}s$$
$$\Delta t_{31}=3.65\cdot 10^{-8}s$$
$$\Delta t_{41}=1.80\cdot 10^{-8}s$$

Solvable system

$$\begin{cases}\sqrt{(x-10)^2+y^2+z^2}-\sqrt{x^2+y^2+z^2}-c\Delta t_{21}\\ \sqrt{x^2+(y-10)^2+z^2}-\sqrt{x^2+y^2+z^2}-c\Delta t_{31}\\ \sqrt{x^2+y^2+(z-10)^2}-\sqrt{x^2+y^2+z^2}-c\Delta t_{41}\end{cases}$$

Numerical solution (Newton's method/OLS) STDOA= (297, 403, 198) m. The error is about 3-4 m**,** which is typical for TDOA with a compact base.

Determination of source coordinates by signal intensity. Environmental parameters. Attenuation coefficients $\Delta=0.002\ m^{-1}$.

Intensity Relations

$$\frac{I_1}{I_i}=\frac{r_i^2}{r_1^2}e^{\Delta(r_i-r_1)}$$

Numerically:

$$\frac{I_1}{I_2}=0.94,\ \frac{I_1}{I_3}=0.92,\ \frac{I_1}{I_4}=0.97.$$

Logarithm of the system

$$\ln\frac{I_1}{I_i}=2\ln\frac{r_i}{r_1}+\Delta(r_i-r_1)$$

Substituting expressions for $r_i(x,y,z)$ yields 3 nonlinear equations. Numerical solution: S_{int}= (305,395, 210) m. The error is greater in intensity, which is typical for the amplitude method.

Weighted average aggregation of results. TDOA is more accurate → weight w_1=0.7. Intensity → weight w_2=0.3.

$$\vec{S} = \frac{w_1 \vec{S}_{TDOA} + w_2 \vec{S}_{INT}}{w_1 + w_2}$$

Coordinate calculation

$$x = \frac{0.7 \cdot 297 + 0.3 \cdot 305}{1} = 299.4\ m$$

$$y = \frac{0.7 \cdot 403 + 0.3 \cdot 395}{1} = 400.6\ \mathrm{m}$$

$$z = \frac{0.7 \cdot 198 + 0.3 \cdot 210}{1} = 201.6\ m$$

Final result

$$S_{final} = (299.4, 400.6, 201.6)\ m$$

Error relative to the true source: ≈2.2 m. Each system separately gives a solution with meter errors. Mid-weighting significantly improves accuracy. The method is stable even with a sensor base of ≤ 10 m and a range of 300-500 m.

The implementation of the proposed method for localizing NMR signal sources in the field is accompanied by a number of factors that significantly affect the accuracy and stability of the solution. The key ones are the geometry of the receiver placement, the level of industrial noise and the uncertainty of the attenuation coefficient in the geological environment.

For TDOA: Waveform distortion leads to timing error; reduced accuracy of time delays; possible false alarms.

For the amplitude method: distortion of the intensity level; increase in the error of exponential approximation; instability of the attenuation coefficient estimate.

For example, at a noise level of 10–15%: the TDOA error increases to 5–10 m, the amplitude method error increases to 20–30 m (*Table 2*).

Table 2 – **Additive Noise Modeling**

No	Noise level	TDOA Error	Amplitude Error	Combined
1	0%	3.7 m	11.2 m	2.2 m
2	10%	5–7 m	15–20 m	3–4 m
3	15%	8–12 m	20–30 m	5–6 m

It follows from the table that the amplitude method is the most sensitive to noise

To reduce the impact of noise, the following methods are used: bandpass filtering in the NMR signal range; coherent signal processing; Shielding of receivers

The practical implementation of the NMR signal localization method requires taking into account a set of factors related to the geometry of the observation system, the level of external interference and the heterogeneity of the geological environment. The most critical are errors caused by receiver placement, industrial noise and variations in the attenuation coefficient.

It is shown that the use of a combined approach (TDOA + amplitude method) can significantly reduce the influence of these factors and ensure acceptable localization accuracy in real conditions.

Results and discussion

As part of the studies performed, the possibility of spatial localization of NMR signal sources during out-of-hole measurements in the Earth's natural magnetic field was analyzed. A case of signal registration by a system of four receivers placed on the day surface of the field and synchronized in time is considered. Such a set of receivers provides redundancy of measurements and allows you to implement independent methods for determining the coordinates of the NMR signal source.

In the first option, the source localization was carried out on the basis of measurements of the time of delay in the arrival of an electromagnetic wave to each receiver relative to the reference channel. At a given average wave velocity in the geological environment, a system of three independent time delays makes it possible to unambiguously determine the spatial coordinates of the source. The analysis showed that this method has a high sensitivity to errors in setting the speed of wave propagation due to its change when crossing the boundaries of geological layers with different electrophysical properties. Even slight variations in velocity lead to systematic shifts in source coordinates estimates.

In the second option, the source coordinates were determined based on measurements of the NMR signal intensity recorded by each receiver. Using an a priori established signal attenuation coefficient in the medium, a system of equations was obtained that relates the distances from the source to the receivers with the measured intensity levels. The results showed that this method is less sensitive to inhomogeneities in the velocity of wave propagation, but is subject to the influence of noise and local attenuation anomalies associated with inhomogeneous fracturing and lithological composition of rocks.

Comparative analysis has shown that both methods have complementary properties. The time delay method provides high accuracy when the velocity model of the medium is correctly specified, while the intensity method is more resistant to velocity errors, but sensitive to variations in the attenuation coefficient. In this regard, a combined approach based on weighted averaging of the coordinates obtained by both methods is implemented in the work. The weights were determined based on estimates of the variances in the errors of each of the localization options.

The simulation results showed that the use of a combined approach can significantly reduce the total error in determining the coordinates of the NMR signal source in comparison with the use of each method separately. Under the conditions of variations in the velocity of electromagnetic waves characteristic of multilayer geological sections, an increase in the stability and unambiguousness of the solution of the localization problem and accuracy relative to the integrated methods is achieved by 30 more percent. The implementation of the proposed method for localizing NMR signal sources in the field is accompanied by a number of factors that significantly affect the accuracy and stability of the solution. The key ones are the geometry of the receiver placement, the level of industrial noise and the uncertainty of the attenuation coefficient in the geological environment.

In addition, it has been established that the use of a fixed set of delay times makes it possible to identify NMR signal sources during their re-recording, which creates prerequisites for coherent accumulation of signals in digital format. This, in turn, leads to an increase in the signal-to-noise ratio and an increase in the reliability of the NMR spectra of weak sources, characteristic of low-porous and poorly saturated reservoirs.

Thus, the results obtained confirm the prospects of the proposed method for localizing NMR sources for the implementation of out-of-hole NMR studies and the creation of spatially distributed systems for monitoring the state and properties of oil reservoirs on the scale of the entire field.

Conclusions

The paper considers the problem of localization of NMR signal sources during out-of-hole studies of the state and properties of oil reservoirs in the Earth's natural magnetic field. It is shown that the lack of spatial reference of NMR signal sources is one of the key factors limiting the practical application of NMR methods for monitoring fields at inter-well and areal scales.

For the first time, a combined method for localizing NMR signals has been proposed, combining time and amplitude parameters of the signal, a mathematical model has been developed that takes into account the geometry of wave propagation and signal attenuation in the medium. A weighted union algorithm has been developed to take into account the accuracy of each method. The stability of the solution under conditions of uncertainty of environmental parameters is shown.

It is established that each of the approaches under consideration has its own advantages and limitations due to the heterogeneity of the geological environment and variations in its electrophysical properties.

The main conclusions of the work are as follows:

1) It is shown that a set of three independent signal arrival delay times is sufficient for unambiguous determination of the spatial coordinates of the NMR signal source at a known average velocity of electromagnetic wave propagation in the medium.

2) It is established that the localization method based on delay times has a high potential accuracy, but is sensitive to errors in setting the velocity model associated with the multilayer structure of the geological section.

3) It is demonstrated that the method for determining the coordinates of the source by measurements of signal intensity and attenuation coefficient is characterized by greater resistance to variations in the velocity of waves, but is subject to the influence of noise and local inhomogeneities of the medium.

4) It is shown that combining the results of the two methods by weighted averaging can significantly reduce the total localization error and ensure the unambiguousness of determining the coordinates of NMR signal sources in real geological and physical conditions.

5) It has been established that the localization of NMR signal sources makes it possible to identify them during repeated measurements and provides conditions for coherent accumulation of signals in digital format, which leads to an increase in the signal-to-noise ratio and an increase in the reliability of the interpretation of NMR spectra.

6) The limitations of the simulation and the need to establish the actual values of the propagation velocity and attenuation coefficient of the electromagnetic wave in anisotropic media are shown.

The results obtained confirm the prospects of using the proposed method as a basis for the development of out-of-hole NMR monitoring systems designed to assess changes in the state and properties of oil reservoirs in the process of field development and the application of enhanced oil recovery methods.

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