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Modulation Effects in Non-Drilling NMR in the Earth's Field

D.V. Trushkin, O.A. Shushakov and A.V. Legchenko

Institute of Chemical Kinetics and Combustion, Novosibirsk, Russia

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Abstract. The paper describes the variant of nuclear magnetic resonance (NMR) in the Earth's field using no prepolarization. This method can be employed to record the NMR signal of underground proton-containing liquids, such as water, located at the depth of more than 100 m without drilling. The non-drilling NMR in the Earth's field is recorded by locating on the surface the circular wire with a diameter of about 100 m. This wire serves as an antenna for the exciting field source and the NMR signal receiver. The radiofrequency pulse with the carrier frequency equal to that of proton resonance in the Earth's field is passed through the wire. When the exciting pulse is switched off, the induction e.m.f. signal caused by the free Larmor nuclear precession in the geomagnetic field is observed. An important case when in the non-drilling NMR in the Earth's field the signal is excited and observed at different frequencies is studied both from theoretical and practical viewpoints. The resulting modulation effects are considered. Such situations arise e.g. either in magnetic rocks or upon magnetic storms.

1. Introduction

The method of nuclear magnetic resonance (NMR) in the Earth's field is used in some physico-chemical and geophysical studies. Packard and Varian [1, 2] were the first to describe this method. There are, however, great problems connected with sensitivity due to a small magnitude of the magnetic Earth's field H_0 known to be a few decimal fractions of Oersted. In the works mentioned, the increase in sensitivity has been obtained due to so-called prepolarization, i.e. using an additional strong magnetic field $H^* \gg H_0$. This principle of registration of NMR signal is used in both laboratory and geophysical methods (the so-called NMR logging) [3].

In 1978 in the Institute of Chemical Kinetics and Combustion, the Siberian Branch of the Russian Academy of Sciences, A.G. Semenov and co-authors have elaborated a setup for recording the NMR signals of underground water and other proton-containing liquids using no boring. NMR was excited by radiofrequency field at resonance frequency. The setup was described in a number of patents [4, 5], etc. Earlier, the similar approach has been proposed by Varian. However, it has not been realized [6].

A circular wire with a diameter of about 100 m is located on the ground to excite and register underground water proton signals. Rectangular pulses of harmonically oscillating current are passed through the wire with frequency equal to that of the Larmor nuclear precession in the geomagnetic field. The exciting pulse is followed by an induction e.m.f. signal caused by the free Larmor precession of water magnetic nuclei in the Earth's field.

At present, the method is widely used for underground water prospecting up to depths of about 100 m. A novel geophysical setup is known as "Hydroscope" [7–9]. It registers the magnetic resonance signal of water protons. In the Earth's field $H_0 \sim 0.5$ Oe, the resonance occurs when the frequency of the external oscillating field H_1 is of about 2.5 kHz. Compared to the conventional geophysical equipment, the selective characteristics of NMR allow the new setup to respond only to the water-containing objects. Other minerals and structures are not manifested.

This method is applied for studying natural objects under natural conditions. Therefore, a number of natural factors affect the NMR signal. The influence of medium conductivity has been studied in [10].

It is interesting to study NMR in the Earth's field upon excitation at the frequencies, differing from the resonance one. The non-resonance conditions of NMR signal excitation arise, e.g., in rocks with magnetic permeability $\mu \neq 1$ as well as in the conditions when the Earth's magnetic field variations (the so-called magnetic storms) take place.

The present paper considers both the NMR in geomagnetic field upon signal excitation at frequencies, differing from the resonance one, and the resulting modulation effects. The model studies of the dependence of the amplitude of modulated NMR signal on the depth of underground watered layer are performed for various durations and intensities of an exciting pulse. The model calculations are compared with the experimental data.

2. Calculation of Underground Water Modulated NMR Signal

Figure 1 schematically depicts the source of exciting field H_1, the water-bearing horizon, and its volume element $\mathrm{d}\,V(\mathbf{R})$ at point the $\mathbf{R}$.

In the geomagnetic field H_0, at thermal equilibrium, the macroscopic magnetic moment $M_0(\mathbf{R})$ oriented parallel to H_0 is equal to [11]:

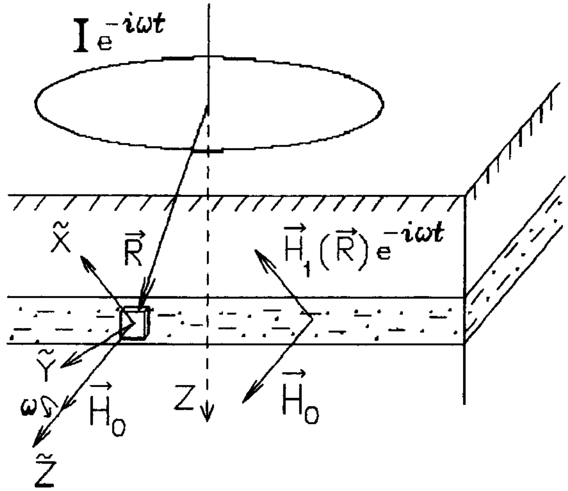

Fig. 1. The scheme showing the location of antenna for exciting and receiving NMR signal and the water-bearing horizon.

$$M_0 = n\frac{\gamma_H^2\hbar^2 I(I+1)}{3kT}|\mathbf{H}_0| , \tag{1}$$

where n is the number of magnetic nuclei per unit volume; I is the nuclear spin; $\hbar$ and k are the Plank and Boltzmann constants, respectively; T is the temperature; γ_H is the magnetogyric ratio for a proton.

In the system of coordinates $O\tilde{x}\tilde{y}\tilde{z}$, rotating around the constant Earth's field $\mathbf{H}_0$ with the frequency ω and axis z parallel to $\mathbf{H}_0$, the vector of the macroscopic nuclear magnetization of the volume element of underground water $\mathbf{M}(\mathbf{R})$, having the components $[0,0,M_0(\mathbf{R})]$ at $t = 0$, after the pulse of oscillating magnetic field will have the following components at $t = t_p$ [11]:

$$\tilde{M}_x(\mathbf{R}) = \frac{\omega_1(\mathbf{R})\Delta\omega}{\omega_{eff}^2(\mathbf{R})}[1 - \cos(\omega_{eff}(\mathbf{R})t_p)]M_0(\mathbf{R}) , \tag{2}$$

$$\tilde{M}_y(\mathbf{R}) = \frac{\omega_1(\mathbf{R})}{\omega_{eff}(\mathbf{R})}\sin(\omega_{eff}(\mathbf{R})t_p)]M_0(\mathbf{R}) , \tag{3}$$

$$\tilde{M}_z(\mathbf{R}) = \frac{(\Delta\omega)^2 + \omega_1^2(\mathbf{R})\cos(\omega_{eff}(\mathbf{R})t_p)}{\omega_{eff}^2(\mathbf{R})}M_0(\mathbf{R}) , \tag{4}$$

where $\omega_0 = \gamma_H|\mathbf{H}_0|$ is the resonance frequency,

$$\Delta\omega = \omega - \omega_0 \tag{5}$$

is the detuning of the resonance frequency; $\omega_1(\mathbf{R}) = 0.5\gamma_H H_{1\perp}(\mathbf{R})$; $\omega_{\text{eff}}(\mathbf{R}) = (\omega_1^2(\mathbf{R}) + (\Delta\omega)^2)^{1/2}$; $H_{1\perp}(\mathbf{R})$ is the component of the oscillating field of the loop perpendicular to $\mathbf{H}_0$. The coefficient 0.5 appears because vector $\mathbf{H}_1$ is polarized linearly rather than circularly.

The component of the macroscopic nuclear magnetization perpendicular to $\mathbf{H}_0$ obeys the expression:

$$|\mathbf{M}_\perp(\mathbf{R})| = (\tilde{M}_x^2(\mathbf{R}) + \tilde{M}_y^2(\mathbf{R}))^{1/2} \,. \tag{6}$$

After the radiofrequency pulse, when the field $\mathbf{H}_1$ is switched off, the $\mathbf{M}_\perp(\mathbf{R})$ vector freely precesses around the geomagnetic field direction with the frequency ω_0. The magnetic field flow from the volume element of underground water $\mathrm{d}V(\mathbf{R})$ is determined using the theorem of mutual induction:

$$\mathrm{d}\Phi(\mathbf{R}) = \frac{1}{I} H_{1\perp}(\mathbf{R})\,|\mathbf{M}_\perp(\mathbf{R})|\,\mathrm{d}V(\mathbf{R}) \,, \tag{7}$$

where I is the exciting current amplitude. A detailed proof of the reciprocity principle for conducting medium is given in [10].

The e.m.f. induction, induced in the loop by the magnetic field of water nuclei, is estimated by integrating over the volume of underground water-bearing layer:

$$e_0(q,\omega) = \omega \int_V |\mathbf{M}_\perp(\mathbf{R})|\, h_{1\perp}(\mathbf{R}) \mathrm{d}V(\mathbf{R}) \,, \tag{8}$$

where $h_{1\perp}(\mathbf{R}) = H_{1\perp}(\mathbf{R})/I$, $q = It_p$ is the exciting current pulse intensity. This is the NMR signal measured.

Underground water is commonly located in the horizontally extended water-bearing layers. In this case $\mathbf{M}(\mathbf{R}) = \mathbf{M}(z)$, where z is the coordinate along the normal to the surface:

$$e_0(q,\omega) = \int_0^{z_{\max}} K(q,\omega,z)\,|\mathbf{M}(z)|\,\mathrm{d}z \,, \tag{9}$$

where
$$K(q,\omega,z) = \omega\int_S h_{1\perp}(\mathbf{R})\mathrm{d}S \ .$$

For the given $q = q^0$, Eq.(3) determines the dependence of the amplitude of underground water NMR signal on the frequency of the oscillating magnetic field whose form depends on the given relations between $\omega_1(\mathbf{R})$, $|\Delta\omega|$ and t_p.

3. Experimental

The NMR signal was measured using the geophysical NMR-tomograph "Hydroscope" developed in the Institute of Chemical Kinetics and Combustion, the Siberian Branch of the Russian Academy of Sciences [4, 5].

Experiments were carried out on the ice of the artificial Ob Lake. Resistivity of water was measured simultaneously and amounted to 47 Ohm · m. According to [10], this value has no effect on the NMR signal. Therefore, in calculations it was neglected. Water was found at the depth from 1 to 14 m.

4. Results and Discussion

Figure 2 presents model calculations of the dependence of the amplitude of underground water NMR signal on the detuning of the exciting frequency, Eq.(9), for horizontal water-bearing layers (aquifers) with thickness 10 m and water content 100%, located at different depths (10–20, 30–40, and 50–60 m). Various durations and intensities of the exciting pulse are considered. The angle of inclination of the geomagnetic field was taken to be 90°, the resonance frequency $\omega_0/2\pi = 2500$ Hz.

Each of the plots in Fig. 2 shows two modulation curves. The solid ones correspond to the exciting pulse intensity at which the first NMR signal maximum is observed at the resonance frequency ($\omega = \omega_0$) from the given aquifer, i.e. magnetization turns through about 90°. The dotted curves correspond to the pulse intensity at which the first NMR signal minimum is observed from the same layer at the resonance frequency, i.e. magnetization turns through about 180°. With $|\Delta\omega| \geqslant 2\pi/t_p$ for both of the curves the characteristic oscillations of signal amplitude are observed with the frequency period $\delta\omega \simeq 1/t_p$.

Note that similar calculations of the NMR signal for homogeneous fields $\mathbf{H}_1$ and $\mathbf{H}_0$ yield similar results.

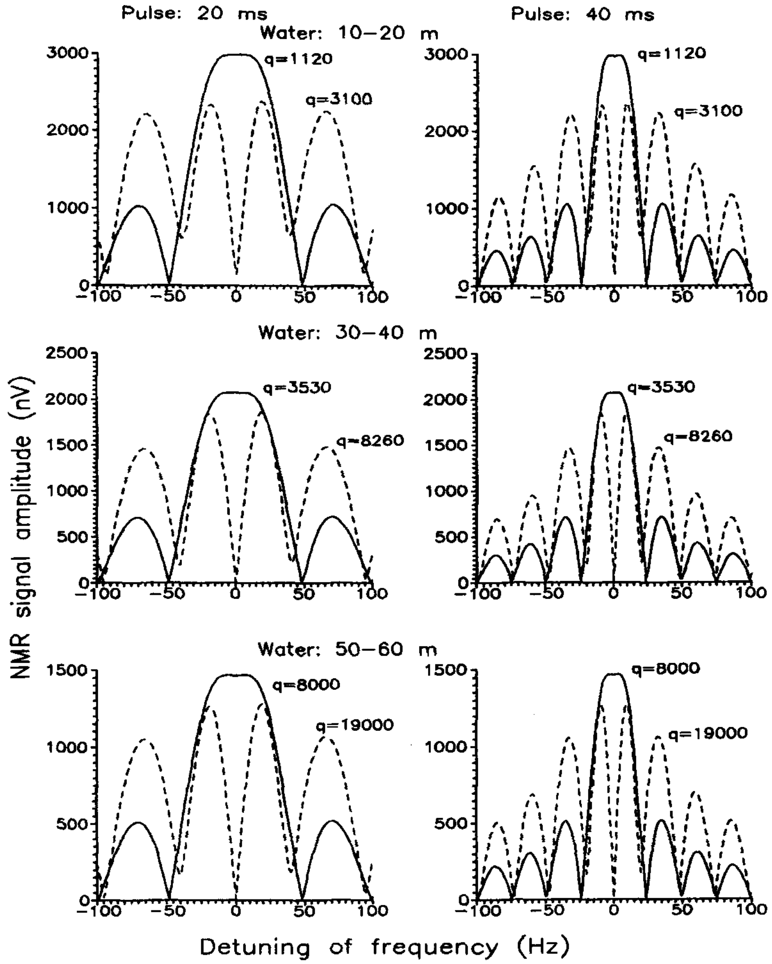

Fig. 2. The dependence of NMR signal amplitude on detuning between resonance and exciting frequencies for different depths of water-bearing layer and various values of intensity and duration of the exciting pulse.

Figure 3 shows the results of the comparison between calculated and experimental data. The angle of inclination of the geomagnetic field was taken to be 72°. Calculations have been performed for the three values of pulse duration: 20, 40, and 80 ms with exciting pulse intensity $q = 468$ A·ms, near the value corresponding to the first NMR signal maximum of the aquifer of 1–14 m. As follows from the figure, the calculation data are in fair agreement with the experimental ones.

The data obtained can be used for non-drilling underground water NMR during magnetic storms when excitation or accumulation of the NMR signal cause the change in the resonance frequency. Besides, they can be applied

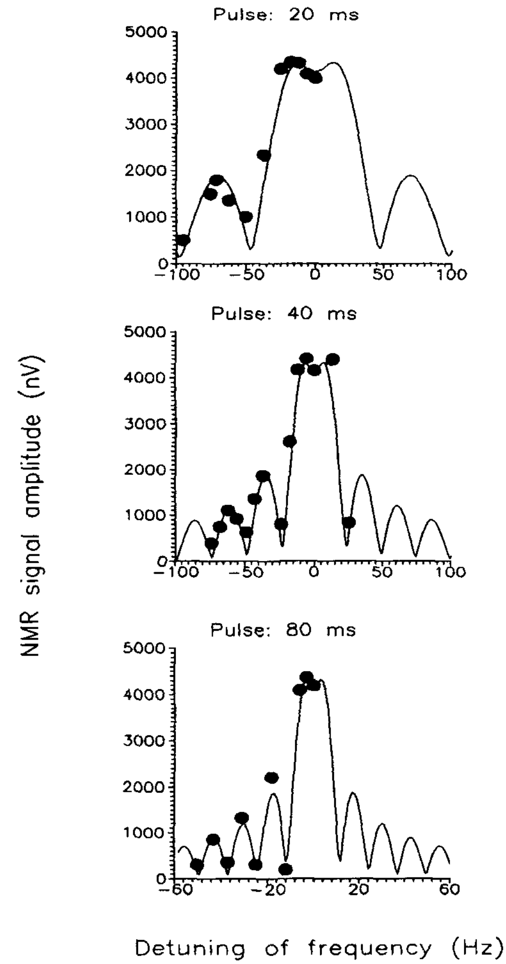

Fig. 3. The dependence of NMR signal amplitude on the detuning between resonance and exciting frequencies: solid line — theoretical data; ● — experimental data obtained on the ice of the artificial Ob Lake.

for prospecting of underground water located in ferromagnetic and diamagnetic rocks with inductivity $\mu \neq 1$, where the magnitude of the geomagnetic field H_0 substantially varies with depth. In addition, the data obtained allow one to substantiate the accuracy of the tuning to the resonance frequency in the equipment used to register non-drilling NMR in the Earth's field.

5. Conclusions

1) NMR has been studied in the geomagnetic field with NMR signal excited and observed at different frequencies. The nature of resulting modulation effects has been investigated.

2) The calculation data on the modulated NMR signal are in fair agreement with the experimental measurements performed on the ice of the Ob reservoir. It is demonstrated that the characteristic frequency of NMR signal oscillations depending on detuning is inversely proportional to the exciting pulse duration.

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Authors address: Dr. Oleg A. Shushakov, Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Sciences, Institutskaya 3, 630090 Novosibirsk, Russian Federation