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The potential of a noise-reducing antenna for surface NMR groundwater surveys in the earth's magnetic field[1]

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Abstract

A method of non-invasive NMR in the earth's field has been developed and is now used for groundwater surveys to depths of investigation of 100 m or more.

A circular wire loop of diameter 100 m, laid out on the ground, is employed to excite and receive the NMR signal in the earth's field. However, in areas with high electromagnetic noise, the NMR measurements may be inaccurate.

To overcome this problem, a noise-reducing figure-of-eight-shaped antenna, consisting of two touching coils each of diameter 50 m, has been utilized.

Using this antenna, the NMR signal has been calculated for different depths of water-saturated layers with various inclinations of the geomagnetic field. The model calculations and experimental data have been compared and found to be mutually consistent. The two-coil antenna is shown to be suitable for studies at depths of up to 30–40 m, which is of practical importance for engineering geology.

Introduction

Varian (1962) proposed applying the effect of nuclear magnetic resonance (NMR) in the earth's field to non-invasive underground fluid prospecting. Semenov *et al.* (1988, 1989) showed the dependence of an NMR signal amplitude on the excition pulse intensity, and proposed using it for determining the distribution with depth of the amount of underground water. In addition, the phase of the NMR signal was thought to give an estimate of water salinity. Semenov *et al.* (1988, 1989) have developed an apparatus for making non-invasive measurements of an NMR signal in the earth's field. This has been named 'hydroscope' and it is the basis for a novel geophysical non-invasive technique used for subterranean water prospecting (Semenov, 1987).

The current Hydroscope equipment uses a circular wire loop of diameter 100 m situated on the ground to excite and receive the NMR signal. Rectangular pulses of

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harmonically oscillating current are passed through the wire at the resonance frequency ω equal to that of proton resonance in the geomagnetic field. The excitation pulse is followed by an e.m.f. induction signal due to the Larmor precession of the water protons in the earth's magnetic field.

The relationship between relaxation time and soil type has been discussed by Semenov (1987) and Schirov, Legchenko, and Creer, (1991) and the effects of variations in the earth's field H_0 have been discussed by Trushkin, Shushakov and Legchenko (1993).

This non-invasive NMR survey technique is sensitive to atmospheric and industrial electromagnetic noise (particularly lightning discharges and magnetic storms, the noise created by power transmission lines and automobile generators).

In this paper an antenna, proposed and tested by Semenov (*) is described and investigated. It consists of two touching coils with currents flowing in opposite directions. The antenna is shaped as figure-of-eight (Fig. 1).

The noise-reducing property of the two-coil antenna utilizes the fact that when recording an NMR signal the external electromagnetic noise induces an e.m.f. in each coil. The e.m.f.s compensate each other because the coils are switched in opposite directions, whereas the NMR signals, induced by underground water, are recorded, to a first approximation, by each coil separately and are then summed.

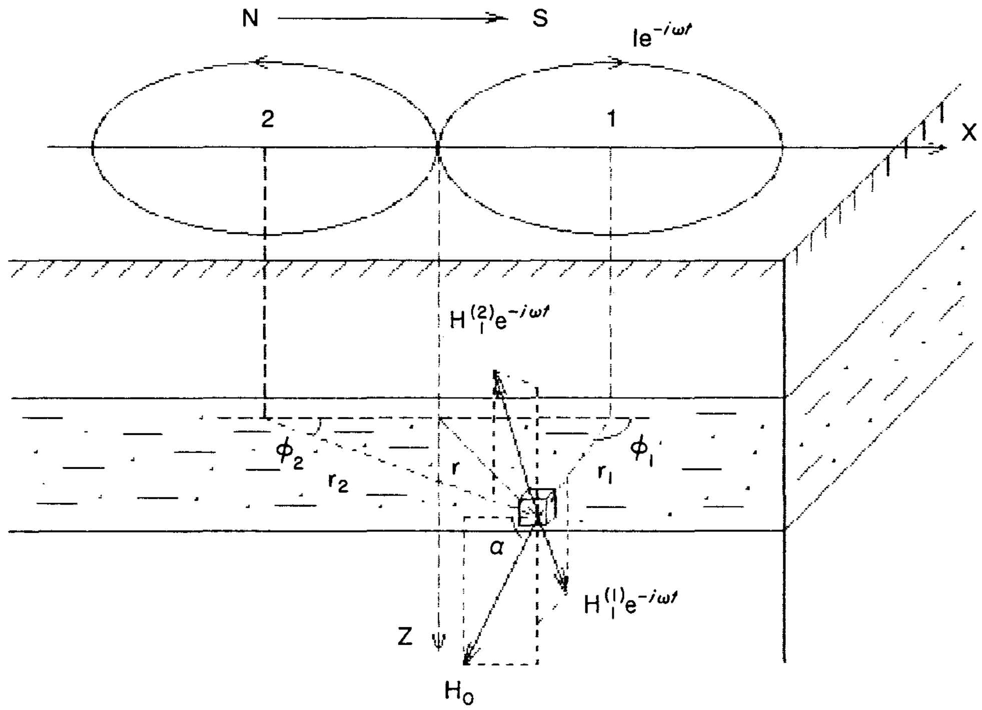

Figure 1. Vector diagram of the magnetic fields of the earth and the two-coil loop when the line, joining the coil centres is oriented from north to south.

Our aim is to study the potential advantages of the two-coil antenna, relative to the conventional loop antenna for non-invasive NMR in the earth's magnetic field, in particular, by numerical computation of the underground water NMR signals. The dependence of NMR signals on the depth of a water-saturated layer has been studied. The model calculations were compared with experimental data.

Calculation of the magnetic field for a two-coil loop

The magnetic field of a circular loop exhibits an axial symmetry about the straight line passing through the centre of the loop perpendicular to its plane. In cylindrical coordinates, the origin coincides with the centre of the loop and the z-axis coincides with the axial axis. Only two components of the magnetic field strength differ from zero, the radial (H_r) and vertical (H_z) components.

The magnetic field of the two-coil antenna has no axial symmetry. The earth's magnetic field displays a different inclination, depending on latitude, since the antenna orientation relative to the geomagnetic field must be taken into account.

The position of the antenna is considered in two directions: from north to south and from west to east.

The NMR signal is dependent on the component of the oscillating magnetic field perpendicular to the constant magnetic field (Abragam 1961), which in this case is the geomagnetic field. The component of the oscillating magnetic field of the two-coil antenna $H_{1\perp}$, perpendicular to the vector H_O of the earth's magnetic field with an arbitrary inclination α at the given point of space r, can be expressed in terms of the Cartesian components of the oscillating magnetic field vector of the two-coil antenna H_1 as follows (see Fig. 1):

$$H_1\perp(r)| = \{H_{1y}^2(r) + (H_{1x}(r) \sin(\alpha) + H_{1z}(r) \cos(\alpha))^2\}^{1/2}. \quad (1)$$

Under the action of a pulse of duration t_p, the equilibrium macroscopic nuclear magnetization M_0 at point r, initially oriented in the direction of the earth's magnetic field, has a vector rotation angle Θ obeying the following expression (Abragam 1961):

$$\Theta(r) = 0.5\gamma_H |H_{1\perp}(r)| t_p,$$

where γ_H is the gyromagnetic ratio of a proton.

Consider now the orientation of the line connecting the coil centres in the north to south direction. At point $r = (r, \phi, z)$ the Cartesian components of the total vector H_1, the oscillating magnetic field of the two-coil antenna, are of the form (see Fig. 1):

$$H_{1x}(r) = H_r[r_1, z] \cos(\phi_1)\text{-}H_r[r_2, z] \cos(\phi_2), \quad (3)$$

$$H_{1y}(r) = H_r[r_1, z] \sin(\phi_1)\text{-}H_r[r_2, z] \sin(\phi_2), \quad (4)$$

$$H_{1z}(r) = H_z[r_1, z]\text{-}H_z[r_2, z], \quad (5)$$

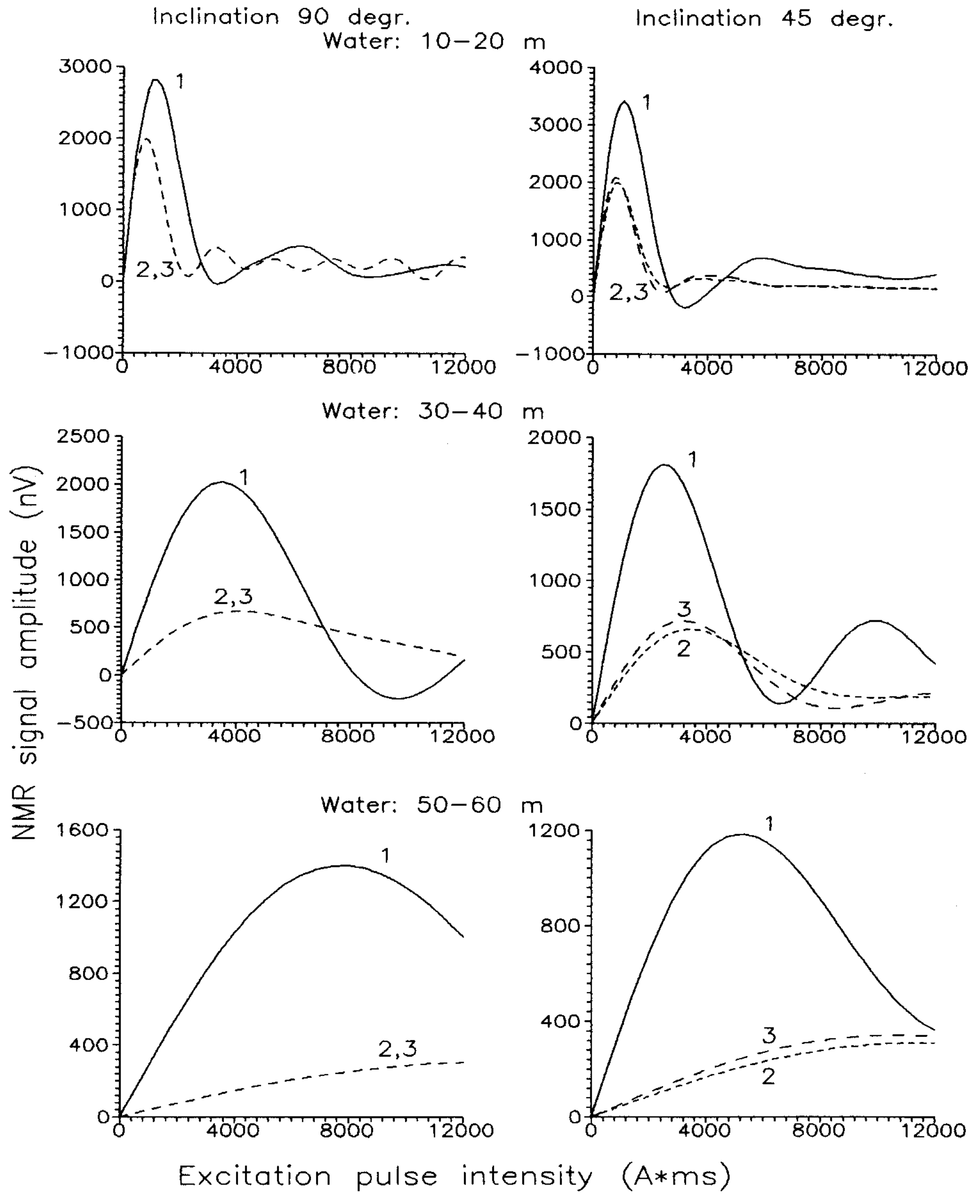

Figure 3. The dependence of the NMR signal amplitude on the excitation pulse intensity for various depths of a water-saturated layer and geomagnetic field inclinations for (1) a circular loop, and (2) a two-coil loop oriented from north to south, and (3) a two-coil loop oriented from east to west.

power transmission lines shows a significant increase (more than 10 times) of the NMR signal-to-noise ratio as the result of using the two-coil antenna.

Calculations were performed for the same parameters of a water-saturated layer. Experiments were carried out at the same location for both a circular-loop antenna of radius 50 m and a two-coil antenna, each coil having a radius of 25 m with the orientation of the line joining the coil centres being (a) from north to south and (b) from east to west.

Figure 4 gives the results of the comparison between experimental and calculated data. Based on the data obtained from a borehole, the calculations were performed for the following three water-saturated layers:

(1) from 35 to 55 m with 23% water content;
(2) from 72 to 85 m with 12% water content;
(3) from 18 to 35 m with 4% water content.

The medium resistivity effect was neglected. The geomagnetic field inclination was assumed to be 75°.

According to Fig. 4, the results obtained from the calculations are in the fair reasonable agreement with the experimental data. Note that at these depths, the two-coil antenna yields, satisfactory NMR signals recorded in field conditions.

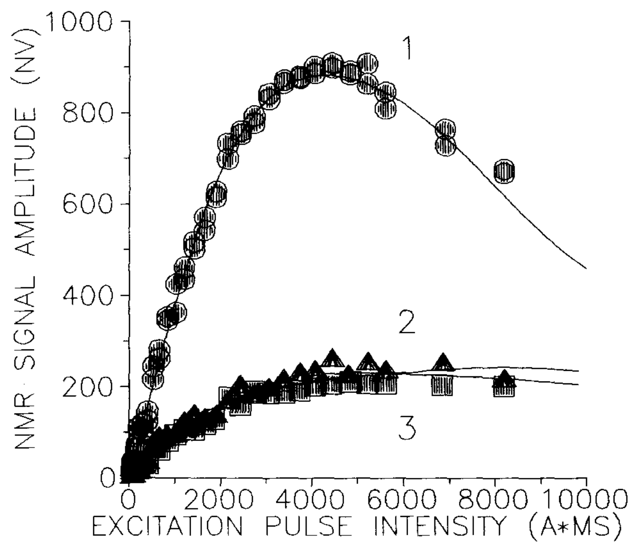

Figure 4. Comparison of experimental and calculation data for the dependence of the NMR signal amplitude on the excitation pulse intensity for borehole #810. Circles denote the experimental data for a circular loop, triangles denote those for the two-coil antenna oriented from north to south, and squares denote those for the two-coil antenna oriented from west to east. The numbers denoting the calculation curves correspond to those in Fig. 3.

Conclusions

The dependence of the NMR signal amplitude recorded by a two-coil antenna, consisting of two touching coils, on the depth of a water-saturated layer has been studied for various inclinations of the geomagnetic field and different antenna orientations. The results of the calculations on the groundwater NMR signal obtained using the two-coil antenna (as the source of the oscillating magnetic field and as the receiver of a free precession signal) are in reasonable agreement with the experimental results.

The NMR signal of the two-coil antenna is less than that of the circular-loop antenna of the same wire length at the same location. Nevertheless the two-coil antenna can be used to investigate water-saturated layers at depths of about 30 – 40 m, which is of practical importance for engineering geology.

The two-coil antenna orientation relative to the earth's magnetic field direction is shown to have a minor effect on the measurement results in the absence of noise. Therefore it is possible to reduce the noise by choosing the proper antenna orientation without it being necessary to correct for the earth's magnetic field direction.

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References

Abragam A. 1961. *The Principles of Nuclear Magnetism.* Oxford University Press.

Semenov A.G. 1987. NMR Hydroscope for water prospecting. *Proceedings of a seminar on Geotomography*, pp. 66–67. Indian Geophysical Union.

Semenov A.G., Burshtein A.I., Pusep A. Yu. and Schirov M.D. 1988. *A device for measurement of underground mineral parameters* (in Russian). USSR Patent 1079063.

Semenov A.G., Schirov M.D., Legchenko A.V., Burshtein A.I. and Pusep A. Yu. 1989. *A device for measuring the parameters of an underground mineral deposit*. GB Patent 2198540.

Schirov M.D., Legchenko A.V. and Creer J.G. 1991. New direct non-invasive groundwater detection technology for Australia. *Exploration geophysics* 22, 333–338.

Trushkin D.V., Shushakov O.A. and Legchenko A.V. 1993. Modulation effects in non-drilling NMR in the earth's field. *Applied Magnetic Resonance* 5, 399–406.