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Feasibility study of a surface-borehole NMR method

by

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Abstract

We present results of a feasibility study of a borehole induction-coil sensor for surface-borehole NMR (nuclear magnetic resonance - SBNMR) investigations. This sensor of 7 cm diameter and 180 cm length is connected to a standard MRS (Magnetic Resonance Sounding) instrument. Thus, SBNMR is a cost-effective extension of the MRS method. Using a downhole sensor increases the depth of investigation and the resolution of MRS. In the near-horizontal Earth's magnetic field, the sensitive area of the sensor is represented by a cylinder of a few meters in diameter. A blind zone of 0.5 to 1 m around the borehole is due to the disturbance of the Earth's magnetic field by the magnetic core of the sensor. The relatively large volume investigated with SBNMR and the blind zone around borehole may represent an advantage of SBNMR over the NMR borehole tool investigating a narrow zone around the borehole. However, using the Earth's magnetic field renders the SBNMR performance site dependent with an inherently low signal-to-noise ratio. Our first results show a good correspondence between SBNMR, MRS and borehole data.

Key words: MRS, SNMR, surface-borehole, water content, SBNMR

Introduction

Selective sensitivity to groundwater is a major advantage of geophysical methods based on the phenomenon of nuclear magnetic resonance (NMR) compared to other geophysical techniques. NMR-based methods can be applied in a borehole or from surface. Downhole, NMR is mainly used in petroleum exploration and production (Dunn et al., 2002); as these tools were initially developed for deep large-diameter boreholes, they are rarely applied to groundwater investigations. However, recent advances in NMR have allowed developing NMR tools adapted to the small-diameter boreholes typical of hydrogeology (Walsh et al., 2013).

Surface NMR (SNMR), also known as Magnetic Resonance Sounding (MRS), is a non-invasive geophysical method (Legchenko and Valla, 2002; Hertrich, 2008; Legchenko, 2013; Behroozmand et al., 2015). MRS and borehole NMR are based on the same physical phenomenon and have many common features, but these methods are not interchangeable (e.g. Müller-Petke et al., 2011). The maximum depth of investigation with MRS is site dependent and rarely exceeds 100 m (Legchenko et al., 1997). The resolution is also variable and progressively decreases with increasing depth (e.g. Girard et al., 2007; Müller-Petke and Yaramanci, 2008; Hertrich et al., 2009; Chevalier et al., 2014; Parsekian and Grombacher, 2015). A limited investigation depth and relatively poor resolution are the properties of MRS (Legchenko and Pierrat, 2014).

Stoeffl (2001) proposed to improve MRS by combining surface and borehole NMR methods. Using a transmitting loop on the surface and a magnetic-field sensor downhole, we obtain surface-borehole NMR (SBNMR). The possibility of using with MRS a small magnetic-field sensor instead of a large loop was demonstrated by Davis et al. (2014) using a SQUID sensor. However, the use of a SQUID sensor for SBNMR is not absolutely necessary and we developed a more traditional induction-coil sensor. Hereafter, we report the first experimental results.

Surface-borehole NMR

Practical implementation of the SBNMR method can be done with a standard MRS instrument equipped with an additional induction-coil sensor in the borehole. Figure 1 shows the measuring setup consisting of a transmitting loop (Tx) on the surface and a sensor in the borehole (Rx).

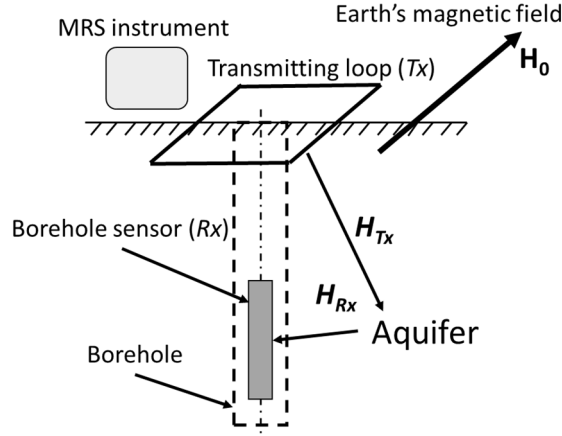


Fig. 1. Transmitting loop on the surface (Tx) and the induction-coil sensor downhole (Rx)

For measuring, a pulse of alternative current oscillating with the Larmor frequency is generated in the transmitting loop, producing the excitation magnetic field H_{Tx} . The pulse is characterized by a pulse moment being a product of the current amplitude and duration. After the pulse is terminated, groundwater generates a magnetic field H_{Rx} , which induces a voltage in the induction coil in the borehole. Both, sensor position and current magnitude in the loop can be varied. Records of the magnetic resonance signal at each combination of sensor depth and pulse moment provide data for interpretation.

Sensor design

Our sensor consists of an open-core coil with a ferrite core (Fig. 2). The coil and connecting cables are protected by electrostatic screens. The sensor is mechanically protected by a plastic tube.

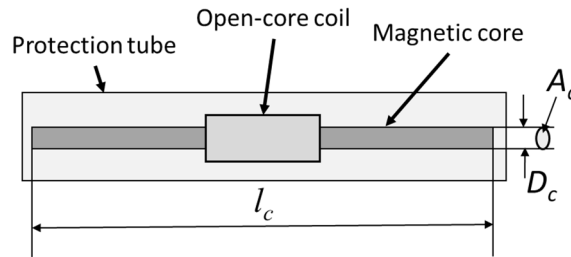


Fig. 2. Design of the borehole sensor (l_c – length of the core, D_c – diameter of the core, A_c – area of the core)

The voltage induced in a coil is given by Faraday's law:

$$V = -\mu_0 \mu_c n A_c \frac{dH}{dt}, \quad (1)$$

82 where $\mu_0 = 4\pi \times 10^{-7}$ H/m, μ_c is the resultant permeability of the core, n is a number of
 83 turns in the coil and A_c is the core cross-section area. The resultant permeability μ_c may be
 84 smaller than the core material permeability μ_r due to the demagnetizing field effect:

$$85 \quad \mu_c = \frac{\mu_r}{1 + N_d(\mu_r - 1)}, \quad (2)$$

86 where N_d is demagnetizing factor that is dependent on the core geometry. It can be estimated
 87 as (Tumanski, 2007):

$$88 \quad N_d \cong \frac{D_c^2}{l_c^2} \left(\ln(2l_c / D_c) - 1 \right), \quad (3)$$

89 where D_c and l_c are the diameter and length of the core, respectively.

90 Thus, the transfer function between the magnetic field and the voltage induced in the coil
 91 depends on the effective area $A_{eff} = n\mu_c A_c$ defined by the magnetic permeability of the
 92 material and the sensor geometry. For estimating the sensor parameters, we considered a
 93 ferrite core with $\mu_r = 2300$ and used Eqs. 1-3. Fig. 3a shows the resultant magnetic
 94 permeability μ_c *versus* core diameter and, considering different core lengths, shows that if
 95 the l_c / D_c ratio increases then $\mu_c \rightarrow \mu_r$. Fig. 3b shows the effective area *versus* the core
 96 diameter, and Fig. 3c demonstrates that for a fixed core length the effective area cannot be
 97 significantly increased by increasing μ_r .

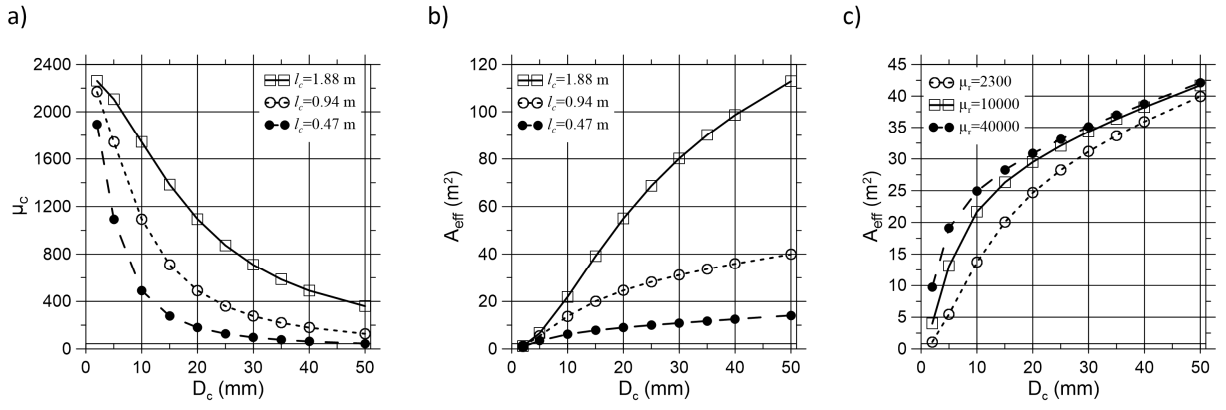


Fig. 3a) The resultant magnetic permeability of the core versus core diameter computed considering different core lengths ($\mu_r=2300$). b) The effective area versus core diameter ($\mu_r=2300$). c) The effective area computed considering different magnetic-permeability values of the material and fixed core length ($l_c=0.94$ m).

Fig. 3 suggests using a long core of large diameter, but sensor dimensions are limited by practical considerations such as the borehole diameter as well as the facility of shipping and handling. To start with, we fabricated a sensor with an external diameter of 70 mm. The core ($l_c=1767$ mm) was made of ferrite bars with dimensions of $27.5 \times 30 \times 93$ mm³ and $\mu_r = 2300 \pm 20\%$ (1840 - 2760) at 25 °C. The ferrite bar geometry is guaranteed by the manufacturer with an accuracy of $\pm 2\%$. Our coil contains 160 turns and has a resistivity of 1.35Ω ; Eqs. 1 to 3 allow computing $A_{eff} = 78.7$ m². For modelling, we can represent the sensor by a magnetic dipole with the respective surface area.

Between 0 °C and 30 °C the ferrite magnetic permeability has an almost linear temperature dependence, changing with a temperature coefficient of 0.7%/°. At 0 °C $\mu_r = 1900$ and at 30 °C it is $\mu_r = 2380$. The corresponding effective area changes from 74.7 m² to 79.4 m² (from -5% to 0.9%) with a consequent impact on the measured voltage. The uncertainty in the magnetic permeability of ferrite causes a corresponding uncertainty in the effective area from 73.9 m² to 82.3 m² (from -4.5% to 6%). Thus, without calibration, variations in core magnetic permeability can cause an uncertainty in measuring voltage of up to $\pm 6\%$.

Noise considerations

The accuracy of the signal measurements depends on the noise level. Electromagnetic noise is generated by different sources, such as the amplifier, the coil wire, the magnetic core

and several other external sources. As the core is not exposed to mechanical or magnetic stress, we exclude a noise due to the Backhausen effect as well as other possible noises generated by the ferrite core. The coil wire produces thermal noise that can be estimated as:

$$V_T = 2\sqrt{k_B T \Delta f R}, \quad (4)$$

where $k_B = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant, T is the temperature, Δf is the bandwidth and R is the wire resistance.

Considering a bandwidth of $\Delta f = 300$ Hz (NUMIS^{poly} MRS instrument), $T = 293$ °K and wire resistance $R = 1.35$ Ω , we obtain a thermal noise of 2.6 nV (0.15 nV/Hz^{-1/2}). This noise can be reduced by lowering the wire resistivity. Amplifier noise reported by MRS instrument manufacturers varies between 0.1 and 1.78 nV/Hz^{-1/2}, yielding a noise voltage varying between 1.7 and 31 nV ($\Delta f = 300$ Hz). In practice, external noise is added to amplifier noise. When using a large loop, the external noise is much larger than the amplifier noise. For example, during our MRS study on the Greenland ice sheet, far from everything (Legchenko et al., 2018), the natural external noise measured with a typical MRS loop (80×80 m²) slightly varied around 100 nV. Such noise may be several times larger during magnetic storms. In built-up areas, manmade noise can be much larger than atmospheric one. However, when using borehole sensors as well as small receiving loops (Grombacher et al., 2018), external noise voltage may be equal to or even smaller than the amplifier noise, and the amplifier design becomes an important issue.

The borehole sensor in laboratory, for which we used an experimental setup shown in Fig. 4.

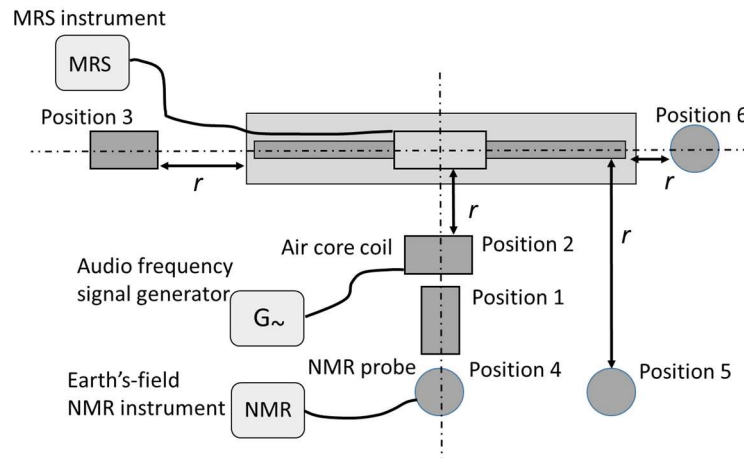


Fig. 4. The experimental setup for measuring parameters of the induction-coil sensor

An Earth's-field NMR instrument with a water sample probe (Clément et al., 2011) evaluated the heterogeneity of the Earth's magnetic field disturbed by the sensor core. Fig. 5 shows the relaxation time T_2^* and the Larmor frequency both characterizing the homogeneity of the Earth's magnetic field. Far from the sensor, the relaxation time was $T_2^*=585$ ms, the Larmor frequency being 1969 Hz. Then, the probe with the water sample was placed at different distances from the sensor (positions 4 to 6), and we measured the Larmor frequency and the relaxation time T_2^* again. At less than 50 cm, the free-induction decay signal (FID) could not be measured because of short T_2^* values; only spin-echo (SE) measurements allowed observing the NMR signal in the vicinity of the sensor. At larger distances, the FID signal was well observed. Our results show that at about 0.5 to 1 m around the sensor the FID signal is well measured, but the relaxation time is shortened and the Larmor frequency is shifted. At 1 to 2 m from the sensor, the measurements are moderately disturbed and beyond 2 m the Earth's magnetic field is only slightly disturbed.

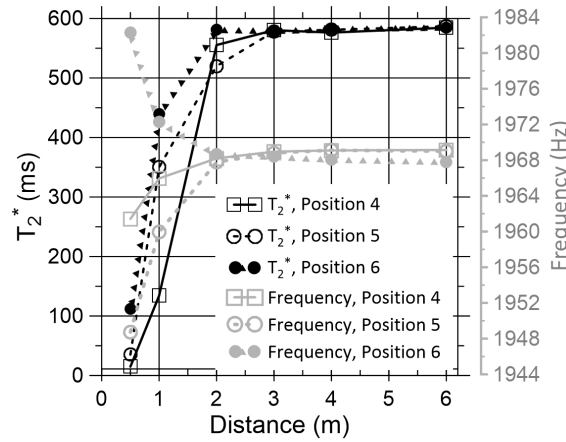


Fig. 5. Relaxation time T_2^* (left vertical axis) and Larmor frequency (right vertical axis) versus distance between sensor and water sample.

Then, the sensor was connected to the MRS instrument. To estimate the max radial extent of the sensitive volume, an audio-frequency generator connected to an air core coil was used for generating a test signal and the MRS instrument applied as a simple voltmeter measured voltage induced in the sensor coil. Both, generator and MRS instrument were tuned to the same frequency of 1969 Hz. We set the coil at different positions around the sensor (positions 1-3) and measured voltage *versus* distance r between coil and sensor. The normalized amplitude of the signal *versus* distance is shown on Fig. 6.

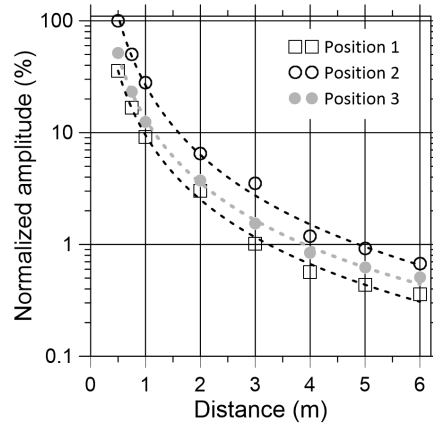


Fig. 6. Normalized amplitude of the test signal measured at different positions of the transmitting coil versus distance between sensor and coil. Dashed lines show the power fit of experimental data.

These measurements show that voltage induced by the test coil rapidly decreased with distance and 6 m from the sensor the amplitude represented only about 0.6% of the initial value measured at 0.5 m. For each position, the measured amplitudes were fitted by a function

$e = a_i / r^b$ (dashed lines). For positions 1 and 3, $b = 1.9$ and for position 2, $b = 2.1$. The fitting

coefficient a_i has individual values for each position. These measurements showed that near

the real sensor, the sensitivity decreases with a rate of approximately $\sim 1/r^2$.

Fig. 6 shows the sensitivity of the sensor to a local signal source (air-core coil). However, the NMR signal is produced by a volume of water around the borehole, which increases as a square function of distance; therefore, the sensitive zone of the sensor can be extended beyond the estimate shown on Fig. 6. However, the volume of water that produces an NMR signal is dependent upon the excitation magnetic field generated by the transmitting loop as well as upon the inclination of the Earth's magnetic field; these parameters are site dependent and required more detailed investigations, which was outside the scope of this study.

Forward modelling

For measuring a magnetic resonance signal from groundwater, an alternating-current pulse with amplitude I_0 and duration τ was generated in the transmitting loop on surface. After switching off the current, the subsurface water generates an exponentially decaying magnetic

field that oscillates with the Larmor frequency ω_0 . The voltage induced in the measuring coil can be calculated as (Weichman et al., 2000; Hertrich et al., 2005):

$$V(q, t) = \int K(\mathbf{r}, q) \int w(\mathbf{r}, T_2^*) \exp(-t/T_2^*) dT_2^* d\mathbf{r} , \quad (5)$$

where $q = I_0 \tau$ is the pulse moment, $w(\mathbf{r}, T_2^*)$ is distribution water in the subsurface and $K(\mathbf{r}, q)$ is the kernel function describing spatial sensitivity. If investigating only the water content, then the initial amplitude of the magnetic-resonance signal is sufficient, and the relaxation term can be omitted. Compared to the MRS method, the depth of the sensor in the borehole introduces an additional parameter that allows improving vertical resolution, and the kernel must be calculated considering each position of the sensor.

Inverse modelling

The MRS inverse problem can be considered as linear, and we approximate the integral equation of Eq. 5 by the matrix equation

$$\mathbf{A}\mathbf{w} = \mathbf{v} , \quad (6)$$

where $\mathbf{v} = v_1, v_2, \dots, v_i, \dots, v_I$ is a set of experimental data, $\mathbf{w} = w_1, w_2, \dots, w_j, \dots, w_J$ is the solution vector and \mathbf{A} is a $I \times J$ matrix representing the kernel of Eq. 5.

We assumed a horizontal stratification (1-D inverse problem) and represented the subsurface by J homogeneous layers. Elements of the solution vector (w_j) represented the water content in corresponding layers. Elements of the data vector v_i included the voltage measured in the receiving coil at each sensor position *versus* pulse moment in the transmitting loop. The total number of measured points $I = \sum_{m=1}^M N_m$, where M is the number of sensor positions and N_m is the number of pulse moments, corresponding to position m . The matrix \mathbf{A} is built in accordance with the measuring procedure.

During our study, we set the sensor at one depth and made measurements for all pulse moments. Then, we changed the depth and repeated the measurements. Note that, compared to MRS, the measurements at each sensor position required fewer pulse moments. One may use only pulse moments corresponding to the maximum sensitivity around the sensor

position. Each element $a_{i,j}$ of matrix **A** was computed with Eq. 5 and contained the amplitude of the magnetic resonance signal corresponding to sensor depth and the value of pulse moment (Fig. 7).

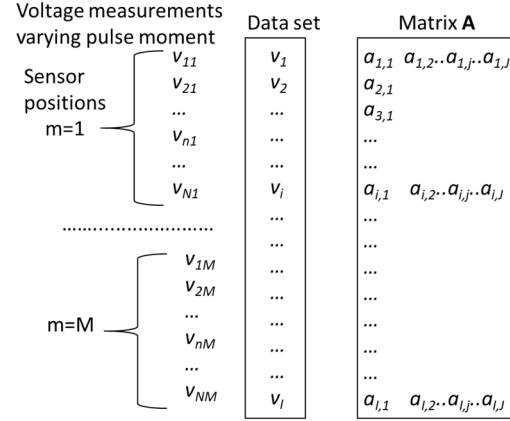


Fig. 7. SBNMR data prepared for inversion.

We used the time-step inversion (Legchenko et al., 2002) based on the Tikhonov regularization method. Other existing algorithms, such as the QT inversion (Mueller-Petke and Yaramanci, 2010), are applicable as well.

Field measurements

For testing the SBNMR method, we performed measurements in the southern part of the Republic of Benin. The township of Abomey Calavi is located between the latitudes 6°20'23.4" and 6°42'6.6" North, and the longitudes 2°14'13.8" and 2°25'7.8" East. At the Ouédo test site, the Tertiary "Continental Terminal" formation is rather irregular, but makes up a good aquifer (Hounsinnou et al., 2014). It is composed of intercalations of fine to coarse sand layers with clay patterns (Lang et al., 1990) shown in Figs. 8a and 8b.

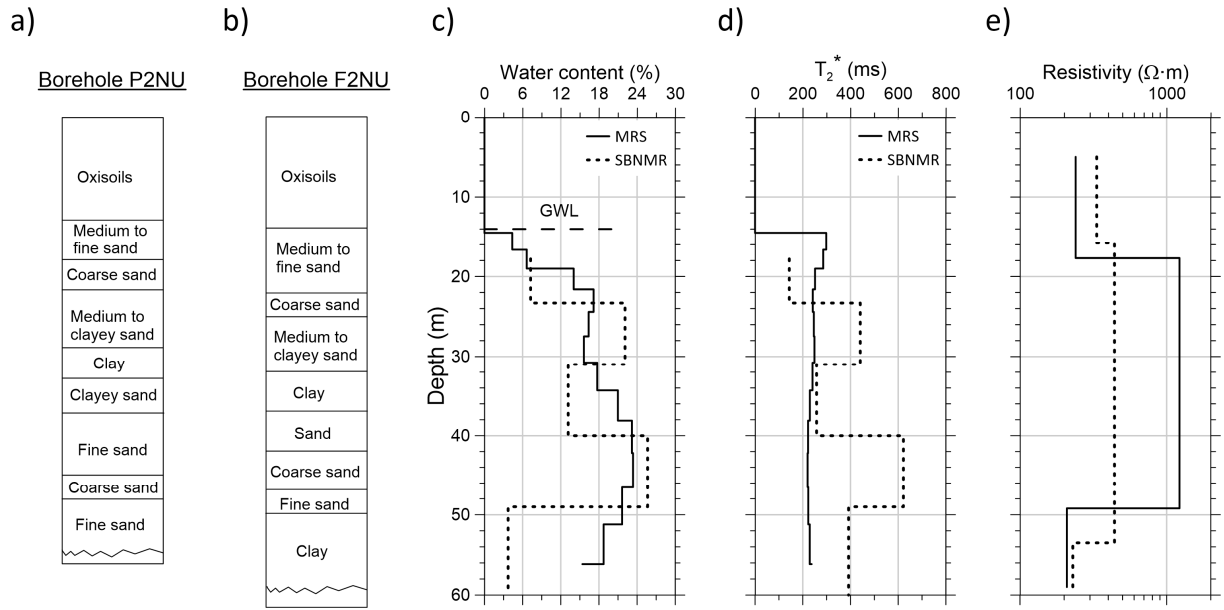


Fig. 8. a,b) Lithological logs of boreholes P2NU and F2NU used for SBNMR experiments. c) Water content distribution provided by MRS sounding (solid line) and by SBNMR measurements (dashed line). d) Corresponding relaxation time T_2^* . e) Electrical resistivity of the subsurface derived from TEM measurements (two equivalent models).

The substratum of this aquifer is composed of continuous clay. The average depth of the substratum, as identified by 15 electrical soundings (VES), is 112 m (90 to 140 m) with an average resistivity of $64 \Omega \cdot m$ (between 200 and $30 \Omega \cdot m$). The aquifer formation has an average resistivity of $380 \Omega \cdot m$ (between 750 and $90 \Omega \cdot m$). Because of the relatively high electrical resistivity and small thickness, the clay layers within the aquifer formation were not resolved by 15 VES and 31 transient EM (TEM) soundings. The average borehole depth is 143 m (110 to 171 m).

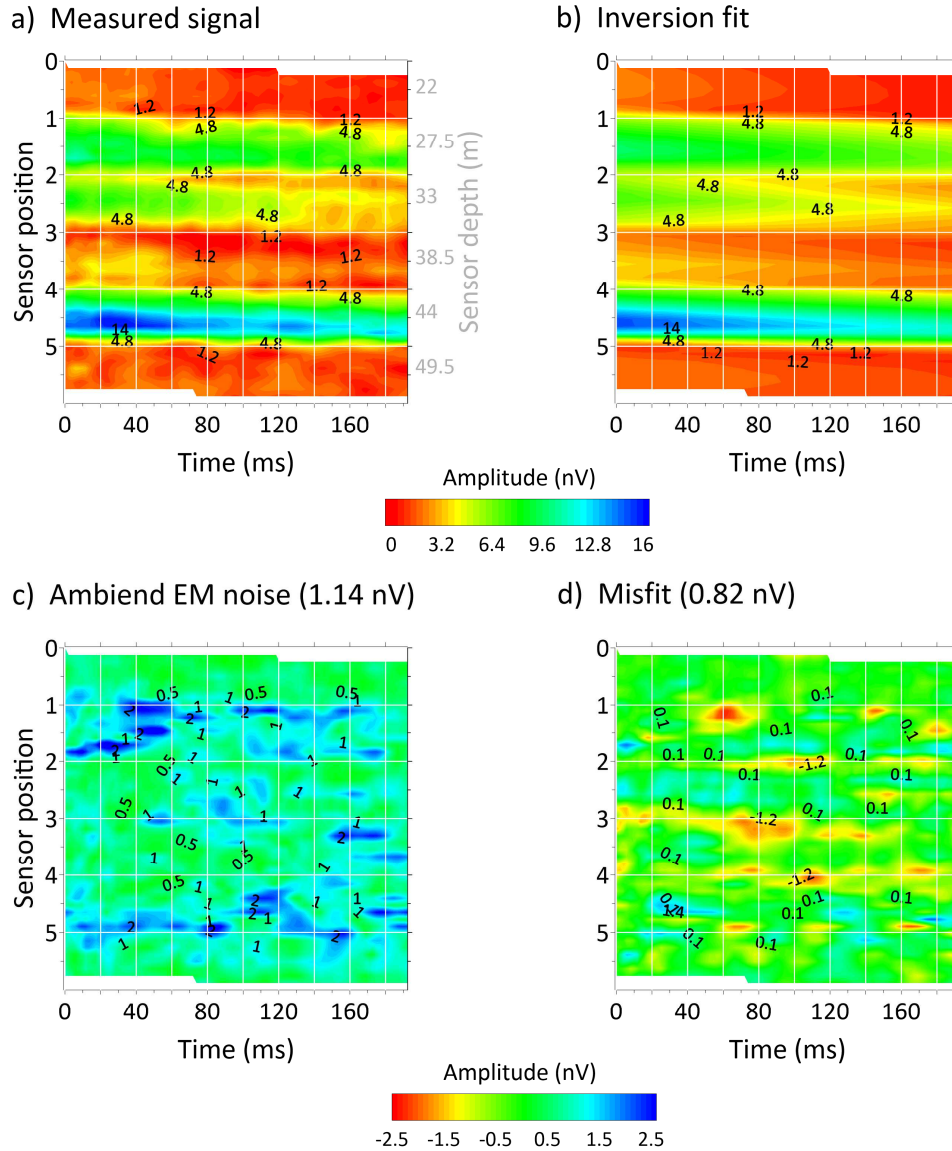
In the study area, the inclination of the Earth's magnetic field is $5^\circ N$ and the Larmor frequency is about 1393 Hz. For our study, we used a commercially available NUMIS^{poly} MRS instrument (Iris Instruments). The induction-coil sensor was placed in borehole F2NU (PVC casing) and the transmitting loop (25-m-side square, 3 turns) was laid out around it. Another borehole (P2NU) was located 10 m from F2NU. An MRS sounding with a coincident figure-eight square loop (62.5-m-side) was set up around borehole F2NU. The length of the cable connecting the instrument and the sensor was 50 m, which defined the deepest position of the sensor. The amplitude of the NMR signal measured with the downhole sensor is a function of both pulse moment and sensor depth. It has a typical for MRS a half-sinus-wave shape. We selected values of the pulse moment individually for each depth so that we always

observed a maximum SBNMR signal. To improve the signal to noise ratio (SNR), we used stacking (usually close to 100). Logging data were not available for these boreholes and we additionally carried out Transient EM (TEM) measurements using a TemFast-48 instrument (AERM) with a coincident 100-m-side square loop. For interpreting the MRS measurements, we used Samovar software (IRD) and for TEM data IX1D v.3.6 (Interpex). The SBNMR data set was processed with experimental software developed by the authors. Figs. 8a and 8b show the lithological logs of two boreholes, ten metres in-between and both located within the transmitting loop. The core analysis shows that both boreholes intersected sand and clay layers, but not at the same levels, demonstrating the lateral heterogeneity of the subsurface. This heterogeneity was neither resolved by MRS sounding (Figs. 8c and 8d) nor by TEM sounding (Fig. 8e). For the MRS and TEM measurements we used large loops and signals from heterogeneous formations were thus averaged. SBNMR shows differences in water content between three zones, but the resolution was insufficient for clearly distinguishing in-between. The sensor was in borehole F2NU and both, high values of the water content (22 and 25%) and long relaxation time (440 and 622 ms) suggest two coarse sand layers (23-31 m and 40-49 m). These layers are separated by a less permeable layer with the average water content of 13% and the relaxation time of 258 ms (31-40 m), identified as clay and sand formations. The correspondence between SBNMR and borehole results is not perfect, which may be explained by the scale factor affecting both data sets. The lithological logs show results corresponding to the layers intersected by the borehole and SBNMR provides information averaged over the volume defined by sensor sensitivity.

Here, we present the SBNMR measurements with the sensor set at six different depths from 22 to 49.5 m. Before stacking and filtering, the noise varied between 20 and 30 nV.

Fig. 9 shows the entire SBNMR data set used for inversion. For each position of the downhole sensor, time series are recorded with a few different values of the pulse moment. Each record consists of measuring ambient EM noise before the pulse and SBNMR signal after the pulse. The dead time between the end of the pulse and the signal recording was 40 ms. Fig. 9a shows time records plotted versus time (0-192 ms) and sensor positions (0-5). The right vertical axis (grey colour) shows the correspondence between the sensor position and the depth of the top of the sensor. For each sensor position, time series are plotted considering normalized pulse moments. For example, a record plotted at the sensor position 0 corresponds to the minimum pulse moment, and the maximum pulse moment corresponds to the position 1 (left vertical axis). Corresponding ambient EM noise records are shown in Fig. 9c. Fig 9b shows theoretical SBNMR signals computed after the inverse model; and Fig. 9d shows the

292 misfit between measured and theoretical signals. The misfit was computed as the root mean
 293 square error between experimental and theoretical time series.



294
 295
 296 *Fig. 9. a) Amplitude of SBNMR signal (colour scale) versus time (after the dead time)*
 297 *recorded at different sensor positions (left vertical scale). For each sensor position, the right*
 298 *vertical axis (grey colour) shows a depth corresponding to the sensor top. b) Theoretical*
 299 *signal computed after the inverse model. c) Noise records corresponding to the same time*
 300 *series. d) The misfit between measured and theoretical signals.*

301
 302 Fig. 10 shows time records extracted from the data shown in the previous figure. Each
 303 graph corresponds to one of the sensor positions. Solid lines show the envelope of the signal
 304 amplitude *versus* time and the dashed lines show the noise amplitude recorded before the

pulse. At all sensor positions, the SBNMR signal clearly dominates noise, thus confirming the feasibility of our SBNMR measurements. These examples also demonstrate pronounced differences between SBNMR signals recorded at different depths corresponding to different geological patterns. Theoretical signals computed after the inverse models fit measured data with the error of 0.82 nV and the mean noise was 1.14 nV.

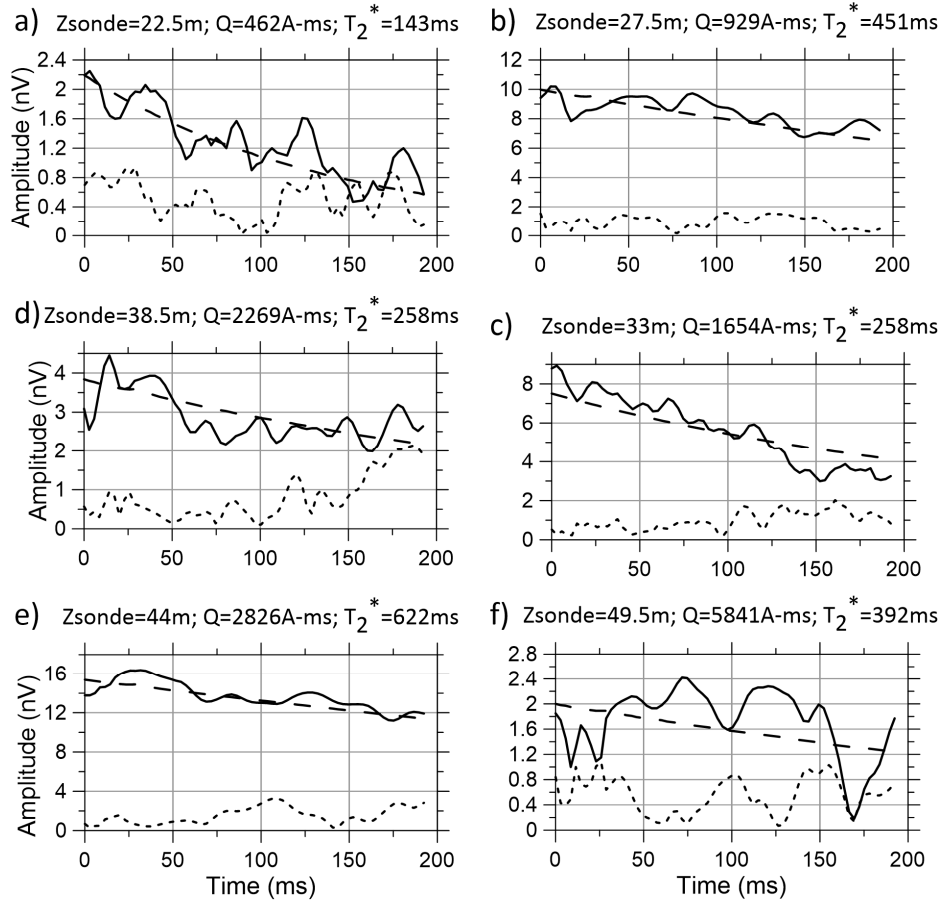


Fig. 10. SBNMR records measured with the sensor located at different depths. Solid lines show the SBNMR signal recorded after the dead time following the pulse, long-dashed lines show inversion fits and short-dashed lines show noise records before the pulse.

Discussion

Our experimental study has confirmed the feasibility of surface-borehole NMR measurements. SBNMR is both similar and different compared to both MRS and borehole NMR, but provides information about groundwater unavailable with the last two methods.

Borehole NMR uses an artificial static magnetic field that allows a high sensitivity. The depth resolution of borehole NMR and the maximum depth of investigation are also much better than with SBNMR and MRS. However, borehole NMR investigates only a narrow zone around borehole, the sensitive area being located within the walls of a cylinder. The diameter

of this (virtual) cylinder (<40 cm) and the wall thickness (<2 mm) are determined by the gradient of the static magnetic field (Dunn et al., 2002). Consequently, hydraulic parameters of the aquifer formation investigated with borehole NMR should be considered as local data. Additionally, some zone around the borehole can be modified by drilling, affecting the results of the study. On the contrary, MRS and SBNMR provide data averaged over large undisturbed volumes.

Operating in the geomagnetic field, MRS and SBNMR both have low sensitivity and a poor signal-to-noise ratio. Results are averaged over a large investigated area that depends on the size of the transmitting loop. SBNMR has better vertical resolution and a potentially larger depth of investigation than MRS. It also better characterizes the investigated aquifer formations in terms of geometry, porosity and hydraulic conductivity. Measurements of both T_1 and T_2 are available with SBNMR as well as with MRS (Legchenko et al., 2004; 2010).

As we have shown the feasibility of this type of measurements, we think that our principal goal was achieved.

Conclusions

We developed and successfully tested in a near-horizontal Earth's magnetic field a borehole sensor for surface-borehole NMR investigations. SBNMR results are averaged over the sensitive area of the sensor that spreads out to a few meters around the borehole. Groundwater at up to 1 m around borehole does not produce a measurable SBNMR signal because of the strong disturbance of the Earth's magnetic field by the magnetic core of the sensor. Similar to MRS, the performance of SBNMR is site dependent and the inherently poor signal-to-noise ratio is comparable to that of MRS.

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References

- Behroozmand, A.A., Keating, K., Auken, E., 2015. A review of the principles and applications of the NMR technique for near-surface characterization. *Surv. Geophys.*, 36(1), 27-85, doi: 10.1007/s10712-014-9304-0.
- Chevalier, A., Legchenko, A., Girard, J.F., Descloitres, M., 2014. 3D Monte Carlo inversion of magnetic resonance measurements. *Geophys. J. Intern.*, 198(1), 216-228, doi: 10.1093/gji/ggu091.
- Clément, R., Legchenko, A., Quetu, M., Descloitres, M., Oxarango, L., Guyard H., Girard, J.F., 2011. Experimental study of a domestic waste material using magnetic resonance measurements. *Near Surf. Geophys.*, 9, 179-185, doi: 10.3997/1873-0604.2010069.
- Davis, A.C., Dlugosch, R., Queitsch, M., Macnae, J.C., Stolz, R., Müller-Petke, M., 2014. First evidence of detecting surface nuclear magnetic resonance signals using a compact B-field sensor, *Geophys. Res. Lett.*, 41, 4222–4229, doi:10.1002/2014GL060150.
- Dunn, K.J., Bergman, D.J., Latorraca, G.A., 2002. *Nuclear Magnetic Resonance Petrophysical and Logging Applications*. Elsevier Science Ltd, UK.
- Girard, J-F, Boucher, M., Legchenko, A., Baltassat, J.M., 2007. 2D magnetic resonance tomography applied to karstic conduit imaging. *J. Appl. Geophys.*, 63, 103-116, doi: 10.16/j.jappgeo.2007.08.0001.
- Grombacher, D., Liu, L., Larsen, J.J., Auken, E., 2018. Practical considerations for small receive coils in surface NMR. *J. Appl. Geophys.*, 154, 81-92, doi: 10.1016/j.jappgeo.2018.04.005.
- Hertrich, M., Braun, M., Yaramanci, U., 2005. Magnetic resonance soundings with separated transmitter and receiver loops. *Near Surf. Geophys.*, 3(3), 131–144, doi:10.3997/1873-0604.2005010.
- Hertrich, M., 2008. Imaging of groundwater with nuclear magnetic resonance. *Prog. Nucl. Magn. Reson. Spectrosc.*, 53(4), 227–248, doi:10.1016/j.pnmrs.2008.01.002.
- Hertrich, M., Green, A.G., Braun, M., Yaramanci, U., 2009. High-resolution surface-NMR tomography of shallow aquifers based on multi-offset measurements. *Geophysics*, 74, G47-G59, doi:10.1190/1.3258342.
- Hounsinnou, P., Mama, D., Alassane, A., Boukari, M., 2014. Hydrogeology and Chemistry Synthesis of the deep Boring of the Township of Abomey-Calavi, Benin. *Res. J. Chem. Sci.*, 4(12), 98-102.

389 Lang, J., Kogbe, C., Alidou, S., Alzouma, K.A., Bellion, G., Dubois, D., Durand, A., Guiraud,
 390 R., Houessou, A., de Klasz, I., Romann, E., Salard-Chebouldaeff, M., Trichet, J., 1990. The
 391 Continental Terminal in West Africa. *J. Afr. Earth Sci.*, 10(1-2), 79-99, doi: 10.1016/0899-
 392 5362(90)90048-J.

393 Legchenko, A.V., Beauce, A., Guillen, A., Valla, P., Bernard, J., 1997. Natural variations in
 394 the magnetic resonance signal used in PMR groundwater prospecting from the surface.
 395 *Eur. J. Environ. Eng. Geophys.*, 2, 173-190.

396 Legchenko, A., Valla, P., 2002. A review of the basic principles for proton magnetic
 397 resonance sounding measurements. *J. Appl. Geophys.*, 50, 3–19., doi: 10.1016/S0926-
 398 9851(02)00127-1.

399 Legchenko, A., Baltassat, J.M., Beauce, A., Bernard, J., 2002. Nuclear magnetic resonance as
 400 a geophysical tool for hydrogeologists. *J. Appl. Geophys.*, 50, 21-46, doi:10.1016/S0926-
 401 9851(02)00128-3

402 Legchenko, A., Baltassat, J.M., Bobachev, A., Martin, C., Robin, H., Vouillamoz, J.M., 2004.
 403 Magnetic resonance sounding applied to aquifer characterization. *J. Ground Water*, 42(3),
 404 363–373, doi: 10.1111/j.1745-6584.2004.tb02684.x.

405 Legchenko, A., Vouillamoz, J.M., Roy, J., 2010. Application of the magnetic resonance
 406 sounding method to the investigation of aquifers in the presence of magnetic materials.
 407 *Geophysics*, 75(6), L91–L100, doi: 10.1190/1.3494596.

408 Legchenko, A., 2013. *Magnetic Resonance Imaging for Groundwater*. Wiley-ISTE 978-1-
 409 84821-568-9.

410 Legchenko A., Pierrat, G., 2014. Glimpse into the design of MRS instrument. *Near Surf.*
 411 *Geophys.*, 12, 297 – 308, doi:10.3997/1873-0604.2014006.

412 Legchenko, A., Miège, C., Koenig, L.S., Forster, R.R., Miller, O., Solomon, D.K., Schmerr,
 413 N., Montgomery, L., Ligtenberg, S., Brucker, L., 2018. Estimating water volume stored in
 414 the south-eastern Greenland firn aquifer using Magnetic-Resonance Soundings. *J. Appl.*
 415 *Geophys.*, 150, 11–20, doi: 10.1016/j.jappgeo.2018.01.005.

416 Müller-Petke M., Yaramanci, U., 2008. Resolution studies for Magnetic Resonance Sounding
 417 (MRS) using the singular value decomposition. *J. Appl. Geophys.*, 66, 165–175, doi:
 418 10.1016/j.jappgeo.2007.11.004.

419 Mueller-Petke, M., Yaramanci, U., 2010. QT inversion — Comprehensive use of the
 420 complete surface NMR data set. *Geophysics*, 75, 4, WA199–WA209, doi:
 421 10.1190/1.3471523.

- Müller-Petke, M., Hiller, T., Herrmann, R., Yaramanci, U., 2011. Reliability and limitations of surface NMR assessed by comparison to borehole NMR. *Near Surf. Geophys.*, 9, 123–34, doi: 10.3997/1873-0604.2010066.
- Parsekian, A.D., Grombacher, D., 2015. Uncertainty estimates for surface nuclear magnetic resonance water content and relaxation time profiles from bootstrap statistics. *J. Appl. Geophys.* 119, 61–70, doi: 10.1016/j.jappgeo.2015.05.005.
- Stoeffl, W., 2001. Use of earth field spin echo NMR to search for liquid minerals. Patent N° US 6,177,794 B1.
- Tumanski, S., 2007. Induction coil sensors—a review. *Meas. Sci. Technol.* 18, R31–R46, doi: 10.1088/0957-0233/18/3/R01.
- Walsh, D., Turner, P., Grunewald, E., Zhang, H., Butler, J.J.Jr., Reboulet, E., Knobbe, S., Christy, T., Lane, J.W. Jr., Johnson, C.D., Munday, T., Fitzpatrick, A., 2013. A small-diameter NMR logging tool for groundwater investigations. *J. Ground Water*, 51(6), 914–926, doi:10.1111/gwat.12024.
- Weichman, P.B., Lavelly, E.M., Ritzwoller M.H., 2000. Theory of surface nuclear magnetic resonance with applications to geophysical imaging problems, *Phys. Rev. E*, 62(1), 1290–1312, doi:10.1103/PhysRevE.62.1290.

Figure captions

- Fig. 1. Transmitting loop on the surface (Tx) and the induction-coil sensor downhole (Rx)*
- Fig. 2. Design of the borehole sensor (l_c – length of the core, D_c – diameter of the core, A_c – area of the core)*
- Fig. 3a) The resultant magnetic permeability of the core versus core diameter computed considering different core lengths ($\mu_r=2300$). b) The effective area versus core diameter ($\mu_r=2300$). c) The effective area computed considering different magnetic-permeability values of the material and fixed core length ($l_c=0.94$ m).*
- Fig. 4. The experimental setup for measuring parameters of the induction-coil sensor*
- Fig. 5. Relaxation time T_2^* (left vertical axis) and Larmor frequency (right vertical axis) versus distance between sensor and water sample.*
- Fig. 6. Normalized amplitude of the test signal measured at different positions of the transmitting coil versus distance between sensor and coil. Dashed lines show the power fit of experimental data.*
- Fig. 7. SBNMR data prepared for inversion.*

Fig. 8. a,b) Lithological logs of boreholes P2NU and F2NU used for SBNMR experiments.
c) Water content distribution provided by MRS sounding (solid line) and by SBNMR
measurements (dashed line). d) Corresponding relaxation time T_2^* . e) Electrical resistivity of
the subsurface derived from TEM measurements (two equivalent models).

Fig. 9. a) Amplitude of SBNMR signal (colour scale) versus time (after the dead time)
recorded at different sensor positions (left vertical scale). For each sensor position, the right
vertical axis (grey colour) shows a depth corresponding to the sensor top. b) Theoretical
signal computed after the inverse model. c) Noise records corresponding to the same time
series. d) The misfit between measured and theoretical signals.

Fig. 10. SBNMR records measured with the sensor located at different depths. Solid lines
show the SBNMR signal recorded after the dead time following the pulse, long-dashed lines
show inversion fits and short-dashed lines show noise records before the pulse.