Field tests of NUMIS$^\text{PLUS}$ MRS equipment in USA (2000-2002): major results

BRGM, USEPA and USGS collaboration project

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Field tests of NUMISplus MRS equipment in USA

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Abstract

Initially developed in Russia, the Magnetic Resonance Sounding method for groundwater investigation (MRS) is directly sensitive to water in the subsurface. Since the MRS method became known in the western world, the US Geological Survey (USGS) and US Environmental Protection Agency (EPA) paid a lot attention to this new technique. In order to evaluate the performance of the MRS, the field tests of Russian production MRS equipment HYDROSCOPE were carried in different parts of the United States in 1993 out by USGS, EPA and Russian Academy of Sciences. Later on, new generations of MRS equipments (NUMIS and NUMISPUS) developed in France by IRIS-Instruments in collaboration with BRGM and Russian Academy of Sciences were tested in 1996, 2000 and 2002.

In this report, the basic principles of the method and the most demonstrative field test results that may allow making idea about possible applications of the MRS method are presented.

Results of MRS application in four test areas of the USA (Arizona, Colorado, Connecticut, and Nevada) with different geology (totally, 21 MRS stations) are presented.

In two areas (Arizona, Colorado), the magnetic resonance signal was not detected with currently available NUMISPUS MRS equipment. These areas are demonstrating the known limitations for the MRS application: aquifers composed of magnetic rocks and very low permeable clay-type material.

In two other areas with aquifers composed of fractured limestone (Nevada) and heterogeneous glacial deposit (Connecticut), MRS results provide quantitative information about aquifers: geometry and hydraulic properties (MRS estimation of the water volume, permeability and transmissivity).
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1. Introduction

The main advantage of the Magnetic Resonance Sounding method (MRS), compared with other geophysical methods for groundwater investigation is that the magnetic resonance signal is generated only by water molecules in the subsurface, what ensures that the MRS method is only sensitive to subsurface water.

Developed in early eighties in Russia (Semenov et al., 1989), MRS equipment HYDROSCOPE has proved that noninvasive characterization of aquifers using magnetic resonance measurements is possible. At that time, MRS was able to provide only the geometry and the water content of water-saturated layers. Now, the experience gained in MRS practical application shows that estimation of the effective porosity and permeability of aquifers is possible using the water content \( w \) and the relaxation time \( T_1 \) derived from MRS measurements. In this aim, results obtained in Nuclear Magnetic resonance Logging (NML) development could be applied to MRS data interpretation. Comparison between results of borehole pumping tests and those of MRS measurements interpretation reveals a good correlation in-between.

Since the MRS method became known in the western world, the US Geological Survey (USGS) and US Environmental Protection Agency (EPA) paid a lot attention to this new technique. In order to evaluate the performance of the MRS, the field tests of Russian production MRS equipment HYDROSCOPE were carried out in different parts of the United States in 1993 by USGS, EPA and Russian Academy of Sciences. Later on, new generations of MRS equipments (NUMIS and NUMISplus) developed in France by IRIS-Instruments in collaboration with BRGM and Russian Academy of Sciences were again tested in USA in 1996, 2000 and 2002. These developments were financially supported by the BRGM research program.

In this report, the most demonstrative results that may allow making idea about possible applications of the MRS method are presented. Unfortunately, the raw data of 1993 fieldwork are not available, and 1996 data were recorded using a different procedure, what makes it difficult the direct comparison between HYDROSCOPE (1993), NUMIS (1996) and NUMISplus (2000 and 2002) results. Thus, only 2000 and 2002 results will be discussed. Taking into account that the MRS remains a rather new technique, the basic principles and some aspects of application of the method are presented (Legchenko et al., 2002a; Legchenko et al., 2002b).

The fieldwork program included MRS measurements, borehole radar and EM logging, magnetic susceptibility mapping, electrical soundings and time domain EM soundings. This report includes only MRS data interpretation.
2. Magnetic resonance sounding method

2.1. THE BASIC PRINCIPLES

A wire loop is employed as a transmitting/receiving antenna. The loop has usually a shape of the square with a side length being between 10 and 150 m, depending on the depth of aquifers. A pulse of alternating current energizes the loop

\[ i(t) = I_0 \cos(\omega_0 t), \quad 0 < t < \tau, \]

where \( I_0 \) and \( \tau \) are respectively the pulse amplitude and duration. The frequency of the current is equal to the Larmor frequency of the protons in the geomagnetic field \( f_0 = \omega_0 / 2\pi = \gamma_p H_0 / 2\pi \text{Hz} \), with \( H_0 \) being the magnitude of the geomagnetic field and \( \gamma_p = 4.257707 \times 10^7 \text{Hz} \) the gyromagnetic ratio for the protons (Slichter 1990). The Larmor frequency depends on the geographical location of the investigated area and varies between 1500 and 2500 Hz around the globe (Legchenko et al., 1997).

\[
\text{The pulse causes precession of the protons around the geomagnetic field, which creates an alternating magnetic field that can be measured using the same antenna after the pulse cut-off. Oscillating with the Larmor frequency, the magnetic resonance signal } e(t, q) \text{ has an exponential envelope and depends on the pulse parameter } q = I_0 \tau 
\]

\[ e(t, q) = e_0(q) \exp(-t / T_2^*(q)) \cos(\omega_0 t + \phi_0(q)), \]

where \( T_2^* \) is the transverse relaxation time, and \( \phi_0 \) is the phase. The initial amplitude \( e_0(q) \) can be calculated as:

\[ e_0(q) = \omega_0 M_0 \int h_{1L} \sin \left( \frac{1}{2} \gamma_p h_{1L} q \right) w(r) dV(r), \]

where \( M_0 \) is the nuclear magnetization for the protons, \( h_{1L} = H_{1L}/I_0 = f(\rho(\rho(r)\alpha), \text{ with } H_{1L} \text{ being the transmitting magnetic field component perpendicular to the geomagnetic field, } \alpha \text{ the geomagnetic field inclination, } \rho(r) \text{ the subsurface resistivity, } 0 < w(r) < 1 \text{ the water content, and } r = r(x, y, z) \text{ the coordinate vector.} \]
In practice, measurement of the signal is not possible before an instrumental delay ("dead time": \( \tau_d \)). Consequently, the initial amplitude \( e_0(q) \) cannot be measured, but obtained by the extrapolation

\[
e_0(q) = e(\tau_d, q) \exp(\tau_d / T_z^*(q)).
\]

The pulse duration for currently available MRS instruments is \( \tau = 40\text{ms} \) and the "dead time", \( \tau_d = 30-40\text{ms} \). This does not allow measuring short signals with \( T_z^* < 30\text{ms} \).

The water distribution in the subsurface \( w(r) \) is a solution of the equation (3). Assuming the horizontal stratification, equation (3) can be simplified to 1D case, and its solution provides the vertical distribution of the water content \( w(z) \) and the relaxation time \( T_z^*(z) \) (Legchenko and Shushakov, 1998; Legchenko et al., 2002a).

The water content derived from MRS data is interpreted as following. Let \( V \) be the total volume of the subsurface; \( V_w \) and \( V_A \), the parts of subsurface filled with water and air respectively, and \( V_R \) the part of subsurface occupied by rocks. Thus, we can write

\[
V = V_w + V_A + V_R.
\]

The water \( V_w \) can be separated into two parts: water \( V_{\text{short}} \), characterized by very short MRS signal which cannot be measured by MRS instrument and water \( V_{\text{long}} \), that produces measurable signal with sufficiently long relaxation time \( (V_w = V_{\text{short}} + V_{\text{long}}) \). Thus, we can define the MRS water content as the part of the total volume of the subsurface occupied by water measurable with MRS:

\[
\frac{V_w}{V} \times 100\%.
\]

The relationship between measured signal \( (e_0(q)) \) and the water content \( (w(z)) \) given by equation (3) was experimentally verified. Field measurements were carried out from the surface of a frozen lake in Russia using HYDROSCOPE equipment (Schirov et al., 1991). Magnetic resonance signal from the bulk water in frozen lake has a long relaxation time \( (T_z^* > 800\text{ms}) \) and hence, all the water contributes to MRS water content. The theoretical signal calculated for a model of 10-m-thick water body \( (w = 100\%) \) derived from a mapping of the lake bottom fits particularly well the initial part of experimental data, where the contribution of the lake water into the total signal is maximal (Fig. 1). As we have no data about aquifers below the lake, we cannot evaluate the MRS results for larger depth.
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Other important characteristic of the magnetic resonance signal are the longitudinal relaxation time $T_1$ and the transverse relaxation time $T_2$ (Slichter 1990). In porous media, the relaxation times $T_1$ and $T_2$ ($T_1 \sim 1.5T_2$) are proportional to the mean pore size (Kleinberg et al., 1994; Kenyon et al., 1997):

$$T_1 \approx \frac{V}{\rho_1 S},$$

where $S$ and $V$ are the surface and volume of pores respectively; and $\rho_1$ is the surface relaxation rate (surface relaxivity) that depends on rock mineralogy. Thus, the relaxation times allow estimation of the mean pore size of water-saturated rock.

The relaxation time $T_2^*$ can be measured using a simple decay of the magnetic resonance signal (equation (2)). However, measurement of $T_1$ and $T_2$ is more complicated and requires of special procedures. Consequently, in MRS, $T_1$ and $T_2$ were not measured, but estimated using the relaxation time $T_2^*$. It is known that $T_2^*$ is proportional to $T_2$, but also depends on local in-homogeneities in the geomagnetic field $\Delta H_0$ caused by rocks (Farrar and Becker, 1971):

$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma \rho (\Delta H_0 / 2).$$

---

Fig. 1 - Comparison of real and simulated data measured over a frozen lake.
For this reason, $T_2^*$ is a less reliable parameter for pore size estimation than $T_1$ or $T_2$. A modification of the well-known double pulse technique which is used in Nuclear Magnetic resonance Logging (NML) for measuring $T_1$ (Dunn et al., 2002) was recently developed also for MRS. A detailed description of this technique would be the subject of a separate paper.

Finally, MRS provides the water content $w(z)$, the relaxation times $T_2^*(z)$ and $T_1(z)$ as functions of depth. Note, that working in 2D or 3D geological environment one must be aware that the information about aquifers derived from MRS data is averaged over antenna size. For example, using a circular loop, we may approximate the area investigated by MRS by a cylinder of $1.5D\pi D$, where $D$ is the loop diameter.

### 2.2. THE DEPTH OF INVESTIGATION

The magnetic resonance signal is sensitive to different natural factors what makes the performance of the method site-dependent. The most common and practically important variations in the magnetic resonance signal are related to the natural geomagnetic field and the electrical conductivity of rocks (Semenov, et al., 1989; Shushakov, 1996; Legchenko, et al., 1997; Valla and Legchenko, 2002). The electrically conductive subsurface attenuates alternative electromagnetic fields by a factor characterized by the "skin depth" that is proportional to $\sqrt{\rho / f}$, where $\rho$ is the resistivity of the subsurface, and $f$ is the frequency of the electromagnetic field. The Larmor frequency used in MRS is proportional to the geomagnetic field magnitude $f_0 \sim H_0$. Consequently, in areas with a low geomagnetic field (towards the equator), the frequency is smaller, and the attenuation caused by the subsurface is less important than in areas with a high geomagnetic field (towards the poles). However, the magnetic resonance response is proportional to square of the geomagnetic field ($E \sim H_0^2$), what improves the signal to noise ratio in areas with a high geomagnetic field even taking into account the attenuation caused by the subsurface. The inclination of the geomagnetic field also modifies the magnetic resonance signal (Legchenko et al., 1997). A numerical demonstration of influence of these natural factors on the maximum depth of investigation of the MRS method is presented in Figure 2. The maximum depth of detection of a one meter thick infinite horizontal layer of water (100% of the water content, and $T_2^* = 1000ms$) in a noiseless environment is depicted versus the half-space resistivity. Calculations were performed for different geomagnetic fields using NUMIS\textsuperscript{PLUS} standard configuration: a square loop with a side of 100 m, a signal detection threshold of 10 nV, and a maximum pulse of 12000 A-ms. We can see that magnitude and inclination of the geomagnetic field is a major factor that defines MRS performance when the subsurface is non-conductive. Influence of electrically conductive layers becomes important when the resistivity of these layers is less than 50 ohm-m approximately.
Inversion of MRS data ($E_{0d}(q)$ and $T_2^*(q)$), provides the depth ($z$), the thickness ($\Delta z$), the water content ($w$), and the relaxation time $T_2^*$ for each water-saturated layer. However, like many other geophysical problems, the MRS inverse problem is ill-posed and therefore the solution is non-unique (Legchenko and Shushakov, 1998). We present “smooth inversion” results performed following the Tikhonov regularization method, but other methods like the linear programming and Monte Carlo inversion could also be used (Guillen and Legchenko, 2002; 2002a).

The resolution of the MRS method decreases with increasing depth. In order to demonstrate the MRS vertical resolution against the depth, we compute MRS signals from an inclined 10-m-thick water-saturated layer that is shown in Figure 3. We assume that soundings are performed along a profile from the deepest part of the layer toward the shallow part. Results of 1D inversion for the water content ($w$), and for the relaxation time ($T_2^*$) are plotted versus the distance (Fig. 4). The dashed lines in the plot show the model. We can see that the resolution degrades progressively with increasing depth. While the top of the layer ($z$) is relatively well resolved down to 100 m, the thickness of the layer is still resolved down to about 60-70 m. Below 70 meters the thickness ($\Delta z$) and the water content ($w$) can not be derived from MRS data. The relaxation time ($T_2^*$) is well resolved down to 100 m for this model.
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Fig. 3 - One layer model.

Fig. 4 - Resolution of the one layer model.
2.3. MRS ESTIMATION OF THE EFFECTIVE POROSITY

Water in porous media can be divided into two parts: capillary-bound water and free water \( (V_a = V_{\text{bound}} + V_{\text{free}}) \). The capillary-bound water \( (V_{\text{bound}}) \) is attached to grain walls and cannot be extracted by gravity. The free water \( (V_{\text{free}}) \) is located at some distance from the grain walls and therefore, can be extracted by gravity. While in the unsaturated zone the capillary-bound water is generally dominating, in the aquifer both capillary-bound and free water are present. In highly permeable water-saturated rocks like sand or gravel, most of the water is free water. On the contrary, in low permeable water-saturated rocks like clays, most of the water is capillary-bound water. Thus, if \( V \) is the total volume, the capillary-bound water corresponds to the moisture content \( \phi_M = (V_{\text{bound}}/V)100\% \). The free water corresponds to the effective porosity \( \phi_E = (V_{\text{free}}/V)100\% \) (Castany, 1982). Therefore, the MRS water content could be written as \( w = c_0 \phi_M + c_1 \phi_E \), where \( c_0 \) and \( c_1 \) are the proportionality coefficients that depend on rock mineralogy and other factors that influence MRS measurements.

Experience of magnetic resonance measurements in porous media shows that capillary-bound water is characterized by short relaxation times and free water by long relaxation times (Chang et al., 1997). In some rocks, capillary-bound water may have \( T_2^* < 30\,\text{ms} \), and free water \( T_2^* > 30\,\text{ms} \). MRS instruments are able to measure only relatively long signals \( (T_2^* > 30\,\text{ms}) \). Thus, it can be stated that in these rocks MRS is sensitive mostly to the free water (Schirov et al., 1991). However, the relaxation time \( T_2^* \) depends on pore size, but also on local in-homogeneities of the geomagnetic field \( \Delta H \) that depend on magnetic properties of water-saturated rock (equation (6)).

Examples of \( T_2^* \) measurement in rocks with different magnetic properties are presented in Table 1 (Legchenko et al., 2002b).

**Table 1 - Magnetic properties of rocks and the relaxation time \( T_2^* \).**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Magnetization (A/m)</th>
<th>Susceptibility (SIU)</th>
<th>( T_2^* ) (ms)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reef limestone (Cyprus)</td>
<td>1.04E-04</td>
<td>-9.14e-6</td>
<td>80</td>
<td>Unsaturated</td>
</tr>
<tr>
<td>Fractured limestone (Cyprus)</td>
<td>2.81E-04</td>
<td>-8.45e-6</td>
<td>130</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Highly fractured limestone (France)</td>
<td>8.11E-03</td>
<td>1.48e-3</td>
<td>280</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Karst limestone (Cyprus)</td>
<td>4.47E-05</td>
<td>-7.17e-6</td>
<td>460</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Clay and fine sand (France)</td>
<td>1.40E-03</td>
<td>1.35e-4</td>
<td>70</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Medium sand (France)</td>
<td>3.90E-04</td>
<td>2.91e-5</td>
<td>120</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Gravel and coarse sand (France)</td>
<td>7.53E-04</td>
<td>4.39e-4</td>
<td>330</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Sandstone (USA)</td>
<td>3.24E-4</td>
<td>1.99e-4</td>
<td>80</td>
<td>Aquifer</td>
</tr>
<tr>
<td>Basaltic gravel (Cyprus)</td>
<td>1.25E-01</td>
<td>4.80e-3</td>
<td>10</td>
<td>Aquifer</td>
</tr>
</tbody>
</table>
One can see that in limestone, signals from both free and capillary-bound water are long ($T^* > 70-80\,\text{ms}$) in comparison with the threshold of MRS instruments ($30\,\text{ms}$). On the contrary, in basaltic gravel, even the signal from free water is very short ($T^* \approx 10\,\text{ms}$) and therefore, cannot be measured. For this reason, measurements in the basaltic gravel were carried out using non-standard MRS equipment, which was especially adapted to the spin echo technique (Farrar and Becker, 1971). In conclusion, in non-magnetic rocks like the limestone, both free and capillary-bound water contribute to MRS water content. In magnetic rocks, even free water cannot be detected. It should be added that other factors like, the surface relaxation rate, temperature and salinity of water may influence MRS measurements (Dunn et al., 2002).

For hydrogeological applications, the MRS water content $w$ can be calibrated as the effective porosity $\phi_E$:

\[ \phi_{\text{MRS}}(z) = C_{\text{fw}} w(z) + C_{\text{bw}}, \]  

(7)

where $C_{\text{bw}}$ and $C_{\text{fw}}$ are the proportionality coefficients between the effective porosity and the MRS water content for capillary-bound and free water respectively. For definition of $C_{\text{bw}}$ and $C_{\text{fw}}$ values, borehole measurements of the moisture content in the unsaturated zone (or in the low permeable part of the subsurface below the water static level) and in the aquifer, as well as measurement of the MRS water content $w(z)$ should be carried out. The calibration can then be performed using one or better more boreholes.

Following the definition of effective porosity, an average volume of free water per surface unit ($\text{m}^3/\text{m}^2$) can be estimated as an integral

\[ V_{\text{MRS}} = \int_{\Delta z} \phi_{\text{MRS}}(z) \, dz, \]  

(8)

where $\Delta z = (z_{\text{bottom}} - z_{\text{top}})$ is the aquifer thickness given by MRS.

Actually, we have no experience in MRS estimation of the effective porosity using equation (7), and this subject still needs some practical confirmation.

### 2.4. MRS ESTIMATION OF THE PERMEABILITY OF AQUIFERS

In Nuclear Magnetic resonance Logging (NML), the permeability of water-saturated porous media can be estimated as (Chang et al., 1997; Kenyon et al., 1997)

\[ k_{\text{NML}} = a\phi_{\text{NML}}^b T_v^c, \]  

(9)
with $k_{\text{NMR}}$ being the permeability estimated using magnetic resonance data, $\phi_{\text{NML}}$ and $T_i$ the porosity and the relaxation time derived from NML measurements, $a, b, c$ empirical constants. Other forms, such as $k_{\text{NML}} = a T_z^b / F^c$, where $a, b, c$ are empirical constants and $F$ is the electrical formation factor, have been also suggested (Wyllie and Spangler, 1952). Both forms work about equally well within experimental error. Basing on equation (8), different estimators have been developed. First, $b = 1$ and $c = 2$ have been proposed (Seevers, 1966). Later on, it has been shown for sandstones that better accuracy can be achieved using $b = 4$ and $c = 2$ (Timur 1968, 1969a, 1969b; Kenyon et al., 1988). In MRS, a form based on equation (9) is actually used:

$$k_{\text{MRS}} = C_p w a T_z^b.$$  \hfill (10)

The effective porosity and permeability of aquifers are scale-dependent parameters. Taking into account that MRS results are averaged over a large area defined by the loop size, the pumping tests, which also provide results averaged over a large volume are used for the calibration. The transmissivity derived from pumping tests is given by the permeability and thickness of the aquifer as: $T_{bh} = k_{bh} \Delta z_{bh}$. Both the permeability and thickness can be also derived from MRS measurements and thus, the MRS transmissivity estimation is:

$$T_{\text{MRS}} = \int k_{\text{MRS}} (z) dz,$$ \hfill (11)

where $k_{\text{MRS}} (z) = C_p w a (z) T_z^b (z)$, and $\Delta z$ is thickness of the aquifer estimated by MRS.

Two estimators based on equation (10) ($\sim w T_z^2$ and $\sim w^4 T_z^2$) were tested using MRS measurements in France (area between Chartres and Orleans). For each estimator the constant $C_p$ was selected so, that MRS estimated transmissivities fit the best the pumping test transmissivities. Results are presented in Figure 5.

![Comparison of pumping test and MRS results](image)

**Fig. 5 - Comparison of pumping test and MRS results:** 1 - $\sim w T_z^2$; 2 - $\sim w^4 T_z^2$ estimators.
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It is obvious, that applied to MRS measurements ($-wT_1^2$) estimator gives much better accuracy in comparison with ($-w^4T_1^2$) estimator. This result is in some contradiction with NML experience, and it can be explained by different reasons:

- **Different conditions of measurement:**
  NML results have been obtained using laboratory measurements on water-saturated sandstone samples of 2 cm in diameter and 4 cm long at the Larmor frequency of 10 MHz (Kenyon et al., 1988). The permeability of the samples was also measured in laboratory. The area investigated by MRS can be approximated by a cylinder of about 80 m high and 100 m in diameter. Measurements were carried out in the geomagnetic field what corresponds to the Larmor frequency of about two kHz. The permeability was measured by pumping tests in boreholes.

- **Different structure of investigated rock:**
  Sandstone samples used for NML calibration have two characteristic dimensions: pore size and pore-throat size (connections between the pores). Pore-throats are smaller in comparison with pores, but the permeability depends on the size of connections between the pores rather than on pore size. Consequently, ($-w^4T_1^2$) estimator, which is more sensitive to pore-throat dimensions, works better in such rocks. Investigated by MRS aquifers are composed of sand, clay, limestone, chalk and weathered granite. Therefore, ($-wT_1^2$) estimator, which is more sensitive to pore volume, is preferable for characterization of highly permeable rocks where the connections between the pores are about as large as pores.

- **Equivalence problem:**
  MRS inverse problem is ill posed. It means that for a particular layer it is not possible to know both the layer thickness and the water content, so is giving rise to layer equivalence. Two layers are equivalent if $w_1\Delta z_1 = w_2\Delta z_2$. For example, a 5-m-thick layer with 7% of the water content and a 7-m-thick layer with 5% of the water content both at the depth of 50 m fit equally well experimental data. Now, using ($-wT_1^2$) estimator we get $T_{MRS1} = C_{p1} w\Delta z T_1^2$ which do not suffer from equivalence problem. Using ($-w^4T_1^2$) form, we get the transmissivity estimation as $T_{MRS2} = C_{p2} w\Delta z T_1^2 w^3$, which will be different for different equivalent solutions. For example, using two equivalent layers from the previous example ($w_1 = 7%; \Delta z_1 = 5m; w_2 = 5%; \Delta z_2 = 7m$) and ($-w^4T_1^2$) estimator, we get the transmissivties $T_{MRS2a} = C_{p2} T_1^2 \cdot 4375$ and $T_{MRS2b} = C_{p2} T_1^2 \cdot 12005$, what makes the
difference equal to \((\text{abs}(T_{\text{MRS1}} - T_{\text{MRS2}})/T_{\text{MRS2}})\times100\% = 63.6\%\). When \((-wT^2)\) estimator is used, result stay unchanged.

It should also be noted that in sandstone, \((-w^4T^2)\) estimator improves the least-square fit between the estimated by magnetic resonance and measured permeability values for about 2.4 times in comparison with \((-wT^2)\) form, which however provides quite reasonable results (Kenyon et al., 1988). Any of listed above reasons or contributions of all of the reasons together may cause the observed difference between NML and MRS results, and thus, we do not consider our results being contradictory to NML experience.

Following the definition of the transmissivity of aquifers, it can be estimated using MRS measurements as:

\[ T_{\text{MRS}} = C_p \int_{0}^{\Delta z} w(z)T^2_1(z)dz, \quad (12) \]

where \(k_{\text{MRS}}(z) = C_p \cdot w(z)T^2_1(z)\) is the MRS estimation of the permeability, and \(C_p = 7.0e-11\) (units: \(w(\%)\) and \(T_1(m\text{s})\)).

In conclusion, we need to discuss the principal limitation of the applicability of MRS to non-invasive estimation of the permeability.

Hydraulic permeability of geological formations is scale-dependent. Samples investigated in laboratories, using borehole NMR tools or performing MRS measurements all have very different scale. Thus, results obtained with these methods might be different. An example of two aquifers of different type is presented in Figure 6.

![Type A and Type B aquifers](image-url)

\textbf{Fig. 6 - Permeability of aquifers: type A – single porosity; type B – double porosity.}
In aquifer with a single porosity (type A), the water is located in similar pores and permeability of this aquifer is closely related to the pore size. In this case, information about the aquifer derived from magnetic resonance measurements is also related to permeability even if investigated samples are of a different volume.

In aquifer with a double porosity (type B) shown in Figure 6, most of the water is located in large pores, but permeability mostly depends on small pores. In this case, if the volume of investigated sample is small (lab. measurements), result of permeability estimation depends on whether the selected sample represents small or large pores. A large-scale method like the MRS will provide us with information mostly related to large pores, as they contain larger quantity of water than small pores. Obviously, the permeability estimation is much less accurate in this case.

In practice, different types of porosity are usually mixed, and measured magnetic resonance signal is often composed of a sum of signals decaying with different relaxation times and thus, contains information about different pores.

2.5. ESTIMATION OF THE ELECTRICAL CONDUCTIVITY OF ROCKS

Electromagnetic losses in a loop on the ground depend essentially on two factors: the resistivity of the wire and the apparent resistivity of the subsurface. Using additional capacitors, the loop may be tuned in resonance. In this case, the electromagnetic losses can be characterized by the Q factor of the resonance circuit. For the same loop and the same frequency, the Q factor is proportional to the apparent resistivity \(Q = \rho_a\). Carrying out measurements of the loop Q factor along a profile, relative variations of the apparent resistivity can be estimated as

\[
\rho_{a_i} \sim \frac{Q_i}{Q_{max}}. \tag{13}
\]

NUMIS system provides measurements of the Q factor with an error of \(+3\%\). However, these data are not calibrated as an apparent resistivity and hence, the Q factor is used only as a qualitative indication of spatial variations of the apparent resistivity. For example, using a typical setup of NUMIS system, the normalized Q factor varies from 1 to 0.5 approximately when passing from 500 ohm-m to 5 ohm-m half-space.

2.6. EXAMPLE OF MRS RESULTS

Example of MRS results obtained in France is presented in (Fig. 7). Investigated aquifer is composed essentially of medium to coarse sand. Field measurements were carried out near a borehole where the pumping tests were fulfilled.
Field tests of NUMIS\textsuperscript{plus} MRS equipment in USA

Fig. 7 - Example of MRS results.

Increase in the water content observed in the MRS log corresponds to the water table indicated by borehole. However, the relaxation time corresponding to this zone is short ($T_1 \approx 50$ ms). It means that the permeability of the rock between 15 and 30 meters is low and that most of the water is capillary-bound water. Increase in the relaxation time corresponds well to top of the aquifer indicated by the lithological log. The MRS permeability estimation also shows that the top of the aquifer is about 15 m below the water static level. A good agreement between the transmissivity estimated by MRS ($T_{\text{MRS}} = 4.7 \times 10^{-3}$ (m$^2$/sec)), and that derived from pumping tests ($T_{\text{bh}} = 4.6 \times 10^{-3}$ (m$^2$/sec)) is observed. Unfortunately, lack of data about the effective porosity does not allow us to calibrate the MRS water content.

2.7. NUMIS\textsuperscript{PLUS} MRS EQUIPMENT

The NUMIS\textsuperscript{PLUS} instrument consists of an oscillating-current generator, a receiver, a PMR signal detector, an antenna and a microprocessor (Fig. 8, 9). The antenna is used for both transmission of the oscillating magnetic field and reception of the PMR signal. The microprocessor switches the antenna from generator to receiver mode by an electronic switch. It also controls the generation of the reference frequency equal to the Larmor frequency. An envelope of the signal from the phase-sensitive detector is recorded by the microprocessor in digital form. A portable PC is used for data processing. The PC is connected to the microprocessor by a standard RS-232 serial link.
Field tests of NUMIS$^{\text{plus}}$ MRS equipment in USA

Fig. 8 - Scheme of NUMIS$^{\text{plus}}$ instrument.

Fig. 9 - NUMIS$^{\text{plus}}$ equipment in a field.
2.8. OUTPUT OF NUMISPLUS SYSTEM

The data interpretation software developed for NUMISplus system is very flexible and provides to users a wide range of possibilities to configure the output page. In this report, the configuration presented in Figure 10 is used.

Site: haddam meadows profile, sounding 7  
Loop: 4 - 37.5  Date: 18.11.2000  Time: 13:13  
NUMIS data set: C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\Haddam_Meadows-2000\HM7.inp  
matrix: C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\MATRX\Had_mead-8sq.mrm  
loop: eight square, side = 37.5 m  
geomagnetic field:  
inclination = 72 degr, magnitude = 53399.06 nT  
filtering window = 198.7 ms  
time constant = 15.00 ms  
average S/N = 2.89; EN/IN = 1.46  
fitting error: FID1 = 17.06%; FID2 = 34.19%  
param. of regular.: modeling  
permeability constant: C_p = 7.00e-09

Fig. 10 - Example of NUMISplus output page.
MRS results are presented by following graphs:

1) **NUMIS signals** - free induction decay signals after the first pulse (FID1) and inversion fits versus the time are arranged by increasing pulse parameter from the bottom to top.

2) **NUMIS inversion** – vertical distribution of the water content with the relaxation time $T_1$ presented by the color scale.

3) **Permeability** – MRS estimation of the permeability versus depth.

4) **Transmissivity** - MRS estimation of the transmissivity versus depth.

5) **$T_1^*(z)$** - vertical distribution of the relaxation time $T_1$.

6) **FID1: $E(q)$** – amplitude of the FID1 signal, inversion fit and an average noise versus the pulse parameter.

7) **$T_1^*$ inversion** – amplitude of the FID1 and FID2 signals and the inversion fit.

8) **FID1: freq($q$)** – the Larmor frequency measured after the first pulse.

9) **Mean signals($q$)** – average through the data acquisition window signals (FID1 and FID2) and the noise.

10) **FID1: $T_2^*(q)$** - relaxation time $T_2^*$ versus the pulse parameter.

11) **FID1: phase($q$)** – phase of the signal measured after the first pulse.

In the header, information about parameters used for the interpretation is presented.

### 2.9. NUMISPLUS DATA: QUALITY ESTIMATION

Currently, the MRS method is able to detect water in aquifers composed of non-magnetic rocks. The magnetic resonance signal may vary from 0 to about 4500 nV (4.5e-6 V). Typical range for Europe is 0 – 500 nV, but for igneous rocks it is 0 – 150 nV. NUMUSplus instrument has an instrumental noise of about 3-5 nV which puts the threshold of reliable measurements of magnetic resonance signal to 5-10 nV approximately.

For MRS data quality estimation, the following parameters can be used:

1) **External noise level after stacking and filtering** is compared with the NUMIS instrumental noise as

$$\frac{EN}{IN} = \frac{(ext.noise)}{(instr.noise)} = \frac{noise}{5}. \quad (14)$$

In ideal case, when the external noise is very small, the $EN/IN$ ratio is about equal to 1. When the magnetic resonance signal is very small, the stacking should be carried out until $EN/IN \leq 1$. When $EN/IN \leq 1$ the sounding can be considered as of a good quality, even if the signal has not been detected.
2) The signal to noise (observed noise includes both external and instrumental noises) ratio

\[
S / N = \text{signal} / \text{noise} \quad (15)
\]

Usually data are considered of a good quality when S/N > 2. In this case, a quantitative interpretation of MRS data is possible, and reliable information about aquifers can be derived from MRS data. When S/N > 2, it is not necessary to have \( EN / IN \geq 1 \).

If \( EN / IN \equiv 1 \) and S/N=1 (signal is not detected), a quantitative interpretation of MRS data is not possible. However, it can be concluded that there is no water (detectable by MRS) in the subsurface. Approximately, the threshold of the detectable water content for NUMIS instrument is about 0.5-1%.

When \( EN / IN > 1 \) and S/N=1, the sounding cannot be considered as of a good quality. The only conclusion can be derived from the data is that the amplitude of the MRS signal is smaller than the noise level. For example, if \( EN / IN = 5 \) and S/N=1, one can conclude that the signal is smaller than 25 nV.

3) The frequency of the MRS signal must be stable and close to the Larmor frequency given by a proton magnetometer. The difference in-between is usually less than 3-4Hz.

4) The phase of the MRS signal must be stable or vary smoothly. The phase helps for discrimination between the MRS signal (phase is stable or vary smoothly) and a cultural noise: the frequency of a cultural noise might stable (but not necessary close to the frequency given by a proton magnetometer) but the phase of noise is always random.

5) The relaxation time \( T_2^* (q) \) is the parameter the most sensitive to data quality. For data of a good quality \( T_2^* (q) \) is stable or varies smoothly between 50 and 400ms.
3. Test sites

In this report we present four areas with different geology that are considered as representative for evaluation of MRS performance. Seven MRS stations were fulfilled in 2000 (Connecticut) and twelve in 2002 (Arizona, Colorado and Nevada).

As not all maps and geological descriptions of test sites were available for writing this report, it is assumed that the exact location of test sites given by appropriate maps and geological/hydrogeological information will be presented in one of following reports.

3.1. SAN LUIS VALLEY (COLORADO)

The location of investigated area in San Luis valley is presented in Figure 11.

![Map of San Luis Valley with Investigated Area Highlighted](image)

*Fig. 11 - Investigated area in San Luis valley.*
Aquifers in this area are essentially composed of fine sand with 1 to 2% of magnetite content. Three sites on the west side of the Great Sand Dunes National Monument were selected:

1) The first one is located at Indian Springs or Big Springs (N37.76609, W105.62511_WGS84). There are two wells 11 meters apart. The water table is at 4.4m in the area;

2) The second site is located in wetlands where the unconfined aquifer is at the surface (N37.78167, W105.63264_WGS84). There is one well at the Wetlands Site. The water table is at 0-0.6m in the area;

3) The third site is located at the terminus of Sans Creek (N37.79620, W105.64829_WGS84). There are three wells in close proximity at the Sand Creek site. The water table is at 3.96m in the area.

3.2. CLANTON RANCH, HEREFORD, PALOMINAS (ARIZONA)

The location of investigated area in Arizona is presented in Figure 12.

Fig. 12 - Investigated area in Arizona.
The geological description of this area is not currently available for this report. Three sites were selected for MRS tests:

1) Clanton Ranch. The water table is at about 5m in the area;
2) Hereford. The water table is at about 5.6m in the area;
3) Palominas. The water table is at about 6.5m in the area.

3.3. ASH MEADOWS (NEVADA)

The location of investigated area in Ash Meadows is presented in Figure 13.

![Map of Ash Meadows with Investigated Area](image)

*Fig. 13 - Location of Ash Meadows test site.*

A detailed hydrogeological study of this area was performed by Dudley and Larson (1976). The aquifers are composed predominantly of limestone and dolomite which transport water freely through fractures that have been enlarged by dissolution of the carbonate minerals. Where they are not fractured, these carbonate rocks have low transmissivities, but throughout the region the unit is broken by fractures and faults that often are enlarged by solution. Above the low carbonate aquifer, there is a Mississippian and Devonian argillite interbedded with coarser clastic rocks and occasional thin limestone of the Eleana Formation. This unit displays low transmissivities even when penetrated for several hundreds meters. The Tippipah Limestone occurs at scattered localities, but has been removed by erosion over most of the area. Where presented beneath the water table, however, it is highly transmissive and was defined as the upper carbonate aquifer.

Location of boroholes in this area is presented in Figure 14.
### Table 2 - Average daily data for selected wells in Ash Meadows

Table 2 summarizes the observations during the pumping tests and hydraulic parameters calculated from the drawdowns in wells that had cascading inflow and measured to some degree. Table 2 captures the drawdown levels in many of the pumped wells by water cascading down the casing from shallow pumps. The hydraulic parameters were conducted during frequent March and April 1971. Drawdown measurements were conducted at different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics. Average rise of the production wells were having different hydrologic characteristics.
3.4. HADDAM MEADOWS (CONNECTICUT)

The location of investigated area in Haddam Meadows is presented in Figure 15.

Fig. 15 - Location of Haddam Meadows test site.
Ten boreholes are available in this area. Location of boreholes and MRS measurements carried out in 1993 is presented in Figure 16 (Lieblich et al., 1994).

![Map showing boreholes and MRS stations in Haddam Meadows.]

**Fig. 16 - Boreholes and 1993 MRS stations in Haddam Meadows.**

Interpretation of the core data, with the aid of ground penetrating radar (Gorin, 1989; Lieblich et al., 1994) was that the progressive retreat of the glaciers, in a northwesterly direction, left:

1) Bedrock overlain by till that changes upwards into poorly sorted ice marginal deposits, which are in turn overlain by deltaic deposits;

---

32
2) En erosional surface cutting into the previous deltaic deposits;
3) Recent (Holocene) river deposits overlying the remaining glacial sediments.

This complex glacial and post-glacial history can explain the significant lateral variations and a poor sorting revealed by boreholes in this area. A general trend of coarsening of glacial deposits with depth is observed in the well and test hole data. Available logs provide no information on the increasing volume fraction of water with depth and are too shallow to verify the configuration of the bedrock surface. Details of the vertical variations may be due to sorting. For example, the qualitative information left out of the generalized log indicates that the gravel interval of TH-23 is “dirty” or poor sorted. One well (JL-1) reached bedrock at approximately 43m.

Well data indicate the water table at about 2m below the surface, slightly less than the elevation of the surface (2.8 ± 0.5m) above sea level (river level) at the site.
4. Results and discussion

Totally, 21 soundings are presented in this report. All MRS measurements were carried out using NUMISPLUS instrument manufactured by IRIS Instruments. The data processing was performed using NUMIS standard interpretation software. The electrical conductivity of rocks was not taking into account. The subsurface was considered as the 50 ohm-m half-space. Results of NUMIS data interpretation are presented in Annexes 1.

Estimation of the quality of MRS data are presented in Table 3. All the data are of a good quality. When the MRS signal is detected (18 soundings), a quantitative interpretation of MRS data reveals the geometry, water content, and permeability of aquifers. In three cases the magnetic resonance signal was not detected. A qualitative interpretation reveals only an estimation of maximum possible MRS water volume inside of the loop area. This estimation only guarantees that it is not possible to have more water than is given by the maximum possible volume. However, it is possible that there is no water at all at this site.

The depth of investigation depends on the antenna size. Three different antennas were used: square of 75-m-size, figure eight square of 37.5-m-size (Trushkin et al., 1994), and figure eight square of 19-m-size. The depth of investigation is about 100, 40 and 20 meters respectively.

**Table 3 - Quality of MRS data.**

<table>
<thead>
<tr>
<th>Test site</th>
<th>Loop</th>
<th>EN/N</th>
<th>S/N</th>
<th>Signal</th>
<th>Interpretation</th>
</tr>
</thead>
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<td>3.2</td>
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<td>1.2</td>
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<td>1.2</td>
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Table 3 - Quality of MRS data (end).

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<th>S/N</th>
<th>Signal</th>
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</table>

4.1. SAN LUIS VALLEY

The test site in the Great Sand Dunes National Park area was selected because of simple hydrogeological situation. Aquifers are shallow and composed essentially of rather homogeneous sand. Number of borehole, with pumping tests performed, are available in this area. Absence of any source of cultural noise (electrical power lines etc.) is also favoring this site. A few successful MRS measurements were performed in the San Luis Valley in 1993 using HYDROSCOPE equipment at some distance from the Sand Dunes. Nobody was anticipating any problem for this site.

However, in the field it was found that the sand contains between 1 and 2% of magnetite. Measurements of the magnetic susceptibility of the sand on the surface revealed values between 4.8e-3 and 12e-3 SIU. It was previously shown (Legchenko et al., 2002b), that in Cyprus the magnetic resonance signal from water in basaltic gravel having similar magnetic susceptibility is too short to be measured by NUMIS equipment (Table 1). A few attempts of measurements near the Sand Dune were however made, but no MRS signal from this water-saturated sand was detected. This result just confirms the theoretically predicted shortening of the $T_2^*$ relaxation time by magnetic rocks and it is in a good agreement with earlier experience.

Then, we put a rectangular loop of 40x110 m around a pool. The pool is filled by the spring and has, after the park rangers, a variable depth from 1 to 3 meters what makes quite large volume of bulk water (Fig. 17). The distance between the loop wire and the water surface is between 2 and 3 meters. After the criteria given in part 1.9, the quality of data is estimated as good ($S/N > 2$, frequency and phase are stable), what allows the quantitative interpretation (Table 3).
Fig. 17 - MRS loop around the Indian Springs pool.

Normally, measuring bulk water in a pool, MRS should reveal a thickness of the water body, the water content of 100%, the relaxation time $T_2^*$ between 800 and 1000 ms (Schirov et al., 1991), and the relaxation time $T_1 \approx (3000 - 5000) \text{ms}$.

MRS data were inverted using a 1D model. The MRS log shown in Figure 18 reveals only water in the pool near the surface ($V_{MRS} = 0.94 \text{m}^3/\text{m}^3$). No water is detected in the sand. As water body in the pool is a 3D object, we should not expect to get a high accuracy of the geometry and water content resolution. However, the MRS water volume (equation 8) is more stable parameter. For example, after the park ranges information about the pool, the water volume in the pool can be estimated as $35 \times 100 \times 2 = 7000 \text{m}^3$. Taking into account that the investigated by MRS area may be approximated by a rectangle of 60 $\times$ 130 m, the volume of water measured by MRS can be estimated as $60 \times 130 \times 0.94 = 7332 \text{m}^3$. Thus, without pretending on high accuracy of our estimation, we consider that water in the pool is correctly resolved by MRS.

The relaxation time $T_1$ measured by NUMIS is in a good agreement with our previous experience. However, the relaxation time $T_2^*$ is much shorter than expected (60-150 ms instead of about 1000 ms). This shortening of the $T_2^*$ can be easily explained by magnetic particles suspended in the water. This measurement is very clear.
demonstration that the magnetic in-homogeneities in water (in rocks) influence the $T_2^*$ relaxation time much more than $T_1$.

Fig. 18 - Indian Spring pool: MRS results

The relaxation time $T_1$ measured by NUMIS is in a good agreement with our previous experience. However, the relaxation time $T_2^*$ is much shorter than expected (60-150 ms instead of about 1000 ms). This shortening of the $T_2^*$ can be easily explained by magnetic particles suspended in the water. This measurement is very clear demonstration that the magnetic in-homogeneities in water (in rocks) influence the $T_2^*$ relaxation time much more than $T_1$.

Experience of MRS application in the Great Sand Dunes test site confirms that actually available equipment NUMIS$^+$ cannot be efficiently used in areas with highly magnetic rocks. In order to avoid such a problem the magnetic susceptibility of rocks should be estimated before making decision of using MRS. We expect, that the threshold of the magnetic susceptibility, below which the MRS can be correctly applied, is about 1e-3 SIU.
Field tests of NUMIS® MRS equipment in USA

4.2. CLANTON RANCH, HEREFORD, PALOMINAS

The quality of data is acceptable \( (EN/IN = 2 \pm 3) \), but no signal was detected \( (S/N \approx 1) \) at all three sites. Aquifers cannot be characterized in this case. Only estimation of maximum possible volume of water can be done (Table 4).

Table 4 - MRS estimation of maximum possible volume of water in Arizona test sites.

<table>
<thead>
<tr>
<th>Test site</th>
<th>( V_{\text{MRS}} ) (m(^3)/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clanton Ranch</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Hereford</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Palominas</td>
<td>&lt;0.2</td>
</tr>
</tbody>
</table>

The absence of MRS signal can be explained by the fact that the subsurface is composed of very fine material, possibly clay. In this case, the relaxation time \( T_2^* \) is too short and MRS is unable to measure this rapidly decaying signal.

4.3. ASH MEADOWS

Location map of MRS stations in the Ash Meadows area and nearby boreholes is presented in Figure 19.

The quality of data is considered as good or acceptable \( (S/N \approx 1.2 \pm 4.7) \). A quantitative interpretation can be carried out for all the soundings.

It may be useful to compare data of Ash Meadows Site 18 with Clanton Ranch data presented earlier. Both data sets are characterized by \( S/N = 1.2 \). However, taking into account that the frequency and the phase of MRS signal at Ash Meadows are stable and at Clanton Ranch they are varying (Fig. 20) we can conclude that at Clanton Ranch the signal was not detected, at Ash Meadows it was.

The difference (DF) between the transmission frequency, which was selected after proton magnetometer measurements of the geomagnetic field and the frequency of received signal (the Larmor frequency), and the phase of the signal are plotted against the pulse parameter. As different loops were used for these measurements, the pulse parameter values are different for these sites what does not change the principal nature of the result.

The external noise estimation after the stacking shows \( EN/IN = 2.8 \) for Clanton Ranch and \( EN/IN = 6.1 \) for Ash Meadows sites respectively (Table 3). Thus, the S/N ratio for Ash Meadows Site 18 sounding could be improved by just increasing the stacking number. At Clanton Ranch, we are already close to the instrumental noise of the instrument and apparently, the amplitude of the MRS signal is below or very close to the threshold of the instrument.
Field tests of NUMIS® MRS equipment in USA

Fig. 19 - Location of MRS station and boreholes in Ash Meadows.

Fig. 20 - Comparison of the frequency and phase.

Large variations in the amplitude of the magnetic resonance signal around Ash Meadows area were observed (Fig. 21). It is a clear indication of a large in-homogeneity of the subsurface.
Fig. 21 - Amplitude of MRS signals in the Ash Meadows area.

Five boreholes are available in investigated by MRS area (Dudley and Larson, 1976). MRS results and corresponding borehole logs are presented in Figures 22-25. Some of MRS sites are close to two boreholes (Fig. 19) and hence, they are compared with different boreholes.

Fig. 22 - Boreholes Inc., 1 and Inc., 2, and corresponding MRS logs in Ash Meadows.
Fig. 23 - Boreholes Inc., 2 and Inc., 3, and corresponding MRS logs in Ash Meadows.

Fig. 24 - Boreholes Inc., 7db2 and Inc., 4, and corresponding MRS logs in Ash Meadows.
Field tests of NUMIS<sup>plus</sup> MRS equipment in USA

Fig. 25 - Borehole Inc., 7db2 and corresponding MRS log in Ash Meadows.

The water content and the permeability sections derived from MRS data along the Profile A are presented in Figure 26.

Fig. 26 - MRS cross-sections in the Ash Meadows area.

Two aquifers are detected by MRS. The shallow aquifer is variable all along the profile. The deeper aquifer was detected only in the eastern part of investigated area.
The MRS transmissivity and water volume for the shallow aquifer, and normalized Q factor observed along the profile are presented in Figure 27.

![Graphs of MRS transmissivity and water volume](image)

**Fig. 27 - MRS results for the shallow aquifer along the Profile A in the Ash Meadows area.**

The subsurface in the eastern part of the profile is more electrically conductive and less hydraulically permeable. It can be explained by a higher content of a fine-grain size material (like clay) in the first 40 meters of the subsurface.

According to hydrogeological study performed by USGS, two limestone aquifers are separated by a low permeable argillite deposit. The upper aquifer is very irregular, but the lower carbonate aquifer is rather extensive all over the area. The absence of the lower carbonate aquifer in MRS logs at south-western part of the investigated area can be explained by a larger depth to this aquifer there. For example, the 30-m-thick lower aquifer is detected by the borehole Inc., 1 at the depth of 70 meters (70-100 m). But boreholes Inc., 3 and Inc., 4 indicate limestone aquifer at the depth of 75-220 m and 82-143 m respectively.

Modeling of MRS signal produced by 30-m-thick aquifer detected by the sounding S18 and borehole Inc., 1 as a function of depth is presented in Figure 28.
Fig. 28 - Amplitude of MRS produced by 30-m-thick limestone aquifer as a function of depth to the top of the aquifer.

According to the modeling results, this aquifer even theoretically cannot be detected below 100 m.

Geologically, the results presented in Figures 26 and 27 can be explained by a fault separating western and eastern parts of the Profile A between MRS stations S18 and S22 (Fig. 29).

The fault is acting as a water tube what may explain a very strong hydraulic link between the well Inc., 2 and Jackrabbit Spring observed during the pumping tests. Division of the Ash Meadows area into the pumping units A and B (Figure 14) is also passing between MRS stations S22 and S18, what is in a good agreement with MRS results.

Summary of MRS results in Ash Meadows area is presented in Table 5.

**Table 5 - MRS results in the Ash Meadows area.**

| Site | Qe|m| Shallow aquifer | Deep aquifer | Total |
|------|------|-----------------|--------------|-------|
|      |      | T<sub>top</sub> (m) | T<sub>bottom</sub> (m) | V<sub>n</sub><sup>s</sup> (m<sup>3</sup>/m<sup>2</sup>) | T<sub>top</sub> (m) | T<sub>bottom</sub> (m) | V<sub>n</sub><sup>s</sup> (m<sup>3</sup>/m<sup>2</sup>) | V<sub>n</sub><sup>s</sup> (m<sup>3</sup>/m<sup>2</sup>) | T<sub>n</sub><sup>s</sup> (m<sup>3</sup>/m<sup>2</sup>) |
| S18  | 0.9  | 8               | 17            | 0.62  | 6e-3 | 50              | 100            | 0.88  | 6e-3 | 1.5   | 1.2e-3 |
| S19  | 0.93 | 4               | 17            | 0.2   | 1e-4 | 50              | 100            | 0.88  | 5.3e-4 | 1.1   | 7e-4   |
| S22  | 0.92 | 4               | 10            | 0.8   | 1.9e-3 | -               | -              | -     | -     | 0.8   | 1.9e-3 |
| S23  | 1    | 3               | 42            | 1.1   | 8.3e-3 | -               | -              | -     | -     | 1.1   | 8.3e-3 |
| S24  | 0.92 | 0               | 30            | 0.63  | 1.3e-2 | -               | -              | -     | -     | 0.63  | 1.3e-2 |
| S28a | 0.85 | 1               | 30            | 0.7   | 2.3e-3 | -               | -              | -     | -     | 0.7   | 2.3e-3 |
| S29  | 1    | 1               | 42            | 1.1   | 1e-2   | -               | -              | -     | -     | 1.1   | 1e-2   |
| S30  | 0.78 | 17              | 35            | 0.33  | 1e-4   | 50              | 100            | 0.4   | 2.4e-5 | 0.73  | 1.2e-4 |

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Field tests of NUMISplus MRS equipment in USA

![Diagram showing water content and MRS permeability](image)

**Geological interpretation**

![Geological interpretation diagram](image)

**Fig. 29 - Geological interpretation of MRS results along Profile A.**

While MRS results are in general good agreement with results of the hydrogeological study carried out by USGS in this area, a few remarks should be made about the accuracy of comparison between MRS and boreholes data:

1) Aquifers in the Ash Meadows area have a complex 2D and 3D geometry, but MRS provides results averaged over antenna size. Accuracy of MRS data interpretation carried out using 1D model in such a case might suffer.
2) Because of limited depth of investigation, MRS provides reliable results down to 50-70 meters. However, the pumping tests carried out in most of the wells in this area were focused on the low carbonate aquifer between 60 and 200 meters barely seen by MRS. The upper carbonate aquifer well characterized by MRS is only qualitatively described by drillers like “easeading water”, “tools fell free” etc.

3) MRS is not a tool for measuring the water static level, but a tool for visualization and characterization of aquifers. The depth to water given by MRS is close to the water static level only for unconfined, horizontal, homogeneous (relatively the loop size) aquifers. It is not always the case in the Ash Meadows area, where some wells are freely flowing.

4.4. HADDAM MEADOWS

Location of MRS stations in the Ash Meadows area is schematically shown in Figure 30.

![Diagram showing the location of MRS loops in the Haddam Meadows area.]

Fig. 30 - Location of MRS loops in the Haddam Meadows area.

Large variations in the amplitude of the magnetic resonance signal around Haddam Meadows area were observed (Fig. 31). These variations can be explained by lateral in-homogeneities of the subsurface.
Fig. 31 - Amplitude of MRS signals in the Haddam Meadows area.

Seven soundings make a profile along the Connecticut River. The water content and the permeability cross-sections derived from MRS data along the profile are presented in Figure 32.

Fig. 32 - MRS cross-sections in the Haddam Meadows area.
An aquifer at a depth between 8 and 25 meters is detected by MRS. The permeability of this aquifer is varying along the profile and has the maximum in its central part.

The MRS transmissivity and water volume, and normalized Q factor observed along the profile are presented in Figure 33.

Fig. 33 - MRS results along the Connecticut River in the Haddam Meadows area.

The much lower permeability and water content of the aquifers in the left-hand side of the profile can be explained by a higher content of the very fine glacial material (till) in the subsurface (Lieblich et al., 1994). The only available information about the subsurface is the grain-size distribution given by a core analysis. While the core data indicate the presence of both, fine and coarse grain size materials all over investigated area, MRS is showing very definitely that depending on sorting, the glacial deposits might have very variable permeability.

According to our practical experience with the MRS applied in different geological situations, the grain-size distribution derived from small-scale borehole data and averaged over antenna size MRS results might provide different information about hydraulic properties of the subsurface, especially in areas with a high geological in-homogeneity. For example, a layer composed of a homogeneous mixture of gravel and clay may have very low permeability when large pores of gravel are fulfilled by clay. However, if in a layer with the same proportion of gravel and clay the gravel deposit is overlaying clay the permeability will be defined by large pores in gravel. For this reason, much more reliable is a comparison of MRS and pumping tests results, both being the large-scale methods sensitive to a pore size in the subsurface.
The electrical conductivity of the subsurface was found to be rather invariable along the profile. For this reason, application of one of electromagnetic/electrical methods might be non-effective. The best and maybe the only way to verify the MRS results would be pumping tests carried our in boreholes situated in two part of the profile having different hydraulic properties.

One should be aware that MRS is not able to identify rocks. It is only estimating the water content (through the amplitude of the MRS signal) and the mean size of pores (through the relaxation time of the signal). However, taking into account the cores data, the geological interpretation could be done. We consider deposits with very low permeability as the “till”, more permeable part of the subsurface as the “fine sand”, and very permeable material as the “medium to coarse sand”.

Proposed geological interpretation of the MRS results along the Connecticut River is presented in Figure 34.
Results of MRS survey in the Haddam Meadows area are summarized in Table 6.

**Table 6 - MRS results in the Haddam Meadows area.**

<table>
<thead>
<tr>
<th>Site</th>
<th>$Q_{norm}$</th>
<th>Top (m)</th>
<th>Bottom (m)</th>
<th>$V_{MRS}$ (m$^3$/m$^2$)</th>
<th>$T_{MRS}$ (m$^2$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
<td>0.98</td>
<td>9</td>
<td>24</td>
<td>0.77</td>
<td>6.8e-3</td>
</tr>
<tr>
<td>S3</td>
<td>0.99</td>
<td>9</td>
<td>24</td>
<td>1.2</td>
<td>4.3e-2</td>
</tr>
<tr>
<td>S4</td>
<td>0.99</td>
<td>12</td>
<td>33</td>
<td>0.13</td>
<td>3e-6</td>
</tr>
<tr>
<td>S5</td>
<td>0.98</td>
<td>13</td>
<td>40</td>
<td>0.16</td>
<td>3.2e-6</td>
</tr>
<tr>
<td>S6</td>
<td>1</td>
<td>5</td>
<td>40</td>
<td>0.3</td>
<td>1.4e-4</td>
</tr>
<tr>
<td>S7</td>
<td>0.97</td>
<td>7</td>
<td>22</td>
<td>0.3</td>
<td>1.4e-3</td>
</tr>
<tr>
<td>S8</td>
<td>0.99</td>
<td>6</td>
<td>19</td>
<td>1.0</td>
<td>3.8e-3</td>
</tr>
<tr>
<td>S9</td>
<td>0.96</td>
<td>5</td>
<td>16</td>
<td>0.67</td>
<td>7e-4</td>
</tr>
<tr>
<td>S10</td>
<td>1</td>
<td>9</td>
<td>18</td>
<td>1.3</td>
<td>2.6e-3</td>
</tr>
</tbody>
</table>
5. Conclusions

Results of MRS application in four test areas of the USA with different geology (21 MRS stations) are presented.

In two areas (Arizona, Colorado), the magnetic resonance signal was not detected with currently available NUMISplus MRS equipment. These areas are demonstrating the known limitations for the MRS application: aquifers composed of magnetic rocks and supposed very low permeable clay-type material. In both cases, MRS cannot be used for the quantitative characterization of the subsurface.

In order to avoid problems with magnetic rocks, we recommend measuring the magnetic susceptibility of the surface material at the initial part of MRS survey, or even better at the planning stage. Rocks with the magnetic susceptibility less than 1.e-3 SIU can be considered as acceptable for MRS application.

Water in a clay-type material having very low permeability is not seen by MRS. In areas where rocks are non-magnetic (k<1e-3 SIU), the absence of MRS signal guarantees with a high degree of reliability the absence of aquifers. However, in hard rock areas, narrow fractures may not be detected by MRS even if borehole crossing it has a significant yield. It can be explained by a small amount of free water in the fracture in comparison with the investigated volume defined by the loop size.

In two areas (Connecticut, Nevada) MRS results provide quantitative information about aquifers: geometry and hydraulic properties (MRS estimation of the water volume, permeability and transmissivity).

In the Ash Meadows area, the hydrogeological study carried out by USGS was focused on the lower carbonate aquifer (70-200 meters). Parameters of the upper aquifer (0-40 meters) are known only approximately. However, the MRS having the depth of investigation of 0-100 meters provide quantitative results mostly about the upper aquifer. While MRS and hydrogeological results are generally in a good agreement, the hydrogeological information is not sufficient for the quantitative verification of the MRS method.

In the Haddam Meadows area, the aquifers is composed by very heterogeneous glacial deposit. The ground truth is derived essentially from cores analysis. However, small-scale data about grain-size distribution provided by core data should be very cautiously used for large-scale MRS results verification. Very reliable MRS data show a strong contrast in the hydraulic permeability along the Connecticut River. Cores analysis only confirms a high variation of grains size in the glacial deposit saying nothing about hydraulic properties of the subsurface. As no electrical contrast was observed all over investigated area, the pumping tests are recommended for the verification of MRS results.
References


ANNEXE

Field results
Site: Sand Dune, Ind. Spring, water pool
Loop: 10 - 75.0    Date: 12.07.2002    Time: 18:37

NUMIS data
C:\mo\REPORTS\usa2002\interpr\Alamosa\pool\SDISPOOL.inp
matrix: C:\mo\REPORTS\usa2002\interpr\Alamosa\matrix\POOL_M.MRM
loop: non-standard, size = 75.0 m
geomagnetic field:
inclination = 65 degr, magnitude = 51995.31 nT
filtering window = 198.6 ms
time constant = 15.00 ms
average S/N = 3.22; EN/IN = 2.74
fitting error: FID1 = 7.33%; FID2 = 44.11%
param. of regular: E,T2* = 495.9; T1* = 0.100
permeability constant C_p = 7.00e-09
Site: Clanton Ranch San Pedro NCA, 18m square 8 antenna
Loop: 4 - 19.0 Date: 26.07.2002 Time: 06:45
NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ARIZONA\Clanton\CLANTON2.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ARIZONA\MATRIX\Arizona-8sq-19.mxm
loop: eight square, side = 19.0 m
geomagnetic field:
inclination = 58 degr, magnitude = 48823.94 nT
filtering window = 198.1 ms
time constant = 15.00 ms
average S/N = 1.22; EN/IN = 2.80
fitting error: FID1 = 37.16%; FID2 = 30.97 %
param. of regular.: E,T2* = 152.6; T1* = 0.954
permeability constant Cp = 7.00e-09
Site: Herford, San Pedro NCA
Loop: 2 - 75.0    Date: 23.07.2002    Time: 07:30

NUMIS data set:
C:\moi\REPORTS\usa2002\interpre\ARIZONA\HERFORD \HERFORD.inp
matrix: C:\moi\REPORTS\usa2002\interpre\ARIZONA\MATRIX\Arizona-
sq.mmm
loop: square, side = 75.0 m
geomagnetic field:
inclination = 58 degr, magnitude = 48220.66 nT
filtering window = 198.6 ms
time constant = 15.00 ms
average S/N = 0.99; EN/IN = 2.10
fitting error: FID1 = 40.54%; FID2 = 67.88%
param. of regular.: E.T2* = 2500.0; T1* = 10.000
permeability constant Cp = 7.00e-09
Site: Palominas, San Pedro NCA 19 m square 8 antenna
Loop: 4 - 19.0   Date: 24.07.2002   Time: 08:30

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ARIZONA\Palominas\PALOMINA.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ARIZONA\MATRIX\Arizona-8sq-19.mrm
loop: eight square, side = 19.0 m
geomagnetic field:
inclination= 58 degr, magnitude= 48701.88 nT
filtering window = 198.6 ms
time constant = 15.00 ms
average S/N = 1.05; EN/IN = 3.10
fitting error: FID1 = 42.54%; FID2 = 42.34 %
param. of regular.: E,T2* = 518.8; T1* = 0.238
permeability constant C_p = 7.00e-09
Field tests of NUMIS MRS equipment in USA

Site: Ash Meadows Site 18
Loop: 2 - 75.0 Date: 18.07.2002 Time: 21:02

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\Site_18.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mrm
loop: square, side = 75.0 m
geomagnetic field:
inclination = 65 degr, magnitude = 49903.76 nT
filtering window = 199.4 ms
time constant = 15.00 ms
average S/N = 1.19; EN/IN = 6.15
fitting error: FID1 = 15.34%; FID2 = 52.12%
param. of regular.: E,T2* = 549.3; T1* = 0.238
permeability constant C_p = 7.00e-09
Site: Ash Meadows Site 19  
Loop: 2 - 75.0  Date: 16.07.2002  Time: 17:53

NUMIS data set:
C:\mo\REPORTS\usa2002\interp\ash_meadows\Ash_Meadows-2002\Site19.inp
matrix: C:\mo\REPORTS\usa2002\interp\ash_meadows\matrix\Ash_mead-sq.mrm
loop: square, side = 75.0 m
geomagnetic field:
inclination= 65 degr, magnitude= 49915.49 nT
filtering window = 199.4 ms
time constant = 15.00 ms
average S/N = 1.71; EN/IN = 1.65
fitting error: FID1 = 13.34%; FID2 = 37.32 %
param. of regular.: E,T2* = 427.2; T1* = 0.238
permeability constant  Cp = 7.00e-09
Site: Point of Rock Spring, site 22  
Loop: 2 - 75.0  Date: 15.07.2002  Time: 16:38

NUMIS data set: C:\mo\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\PTRKSPR.inp
matrix:  C:\mo\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mmm
loop: square, side = 75.0 m
geomagnetic field:
inclination = 65 degr, magnitude = 49903.76 nT

filtering window = 199.4 ms
time constant = 15.00 ms
average S/N = 1.97; EN/IN = 3.27
fitting error: FID1 = 9.61%, FID2 = 38.93%
param. of regular.: modeling
permeability constant Cp = 7.00e-09
Site: Ash Meadows Site 23  
Loop: 2 - 75.0  Date: 18.07.2002  Time: 14:34

NUMIS data set:  
C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\SITE_23.inp  
matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mrm  
loop: square, side = 75.0 m  
geomagnetic field:  
inclination = 65 degr, magnitude = 49903.76 nT  
filtering window = 199.4 ms  
time constant = 15.00 ms  
average S/N = 4.66; EN/IN = 1.91  
fitting error: FID1 = 7.74%; FID2 = 45.97%  
param. of regular: modeling  
permeability constant Cp = 7.00e-09
Site: Ash Meadows Site 24 Reoccupation
Loop: 2 - 75.0  Date: 18.07.2002  Time: 18:25

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\SITE24A.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mrm
loop: square, side = 75.0 m
geomagnetic field:
inclination= 65 degr, magnitude= 49903.76 nT
filtering window = 199.4 ms
time constant = 15.00 ms
average S/N = 2.94; EN/IN = 2.22
fitting error: FID1 = 8.07%, FID2 = 47.85 %
param. of regular.: E;T2* = 600.0; T1* = 10.000
permeability constant Cp = 7.00e-09
Site: site 28 Ash meadows
Loop: 2 - 75.0 Date: 16.07.2002 Time: 23:29

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\ST28.inp
Matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead
sq.mmm
loop: square, side = 75.0 m
gemagnetic field:
inclination = 65 degr, magnitude = 49859.15 nT
filtering window = 199.6 ms
time constant = 15.00 ms
average S/N = 1.83; EN.IN = 4.46
fitting error: FID1 = 15.30%; FID2 = 43.61%
param. of regular: E,T2* = 700.0; T1* = 5.000
permeability constant Cp = 7.00e-09
Site: Ash Meadows Site 29
Loop: 2 - 75.0  Date: 18.07.2002  Time: 16:28

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\SITE_29.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mmm
loop: square, side = 75.0 m
g geomagnetic field:
inclination = 65 degr. magnitude = 49903.76 nT
filtering window = 199.4 ms
time constant = 15.00 ms
average S/N = 3.83; EN/IN = 1.85
fitting error: FID1 = 8.81%; FID2 = 18.40 %
param. of regular: $E, T2^* = 500.0; T1^* = 5.000$
permeability constant $C_p = 7.00e-09$
Site: Ash meadows, site 30
Loop: 2 - 75.0  Date: 16.07.2002  Time: 03:33

NUMIS data set: C:\moi\REPORTS\usa2002\interpr\ash_meadows\Ash_Meadows-2002\AM_S30.inp
matrix: C:\moi\REPORTS\usa2002\interpr\ash_meadows\matrix\Ash_mead-sq.mrm
loop: square, side = 75.0 m
geomagnetic field:
  inclination= 65 degr, magnitude= 49903.76 nT
  filtering window = 199.4 ms
  time constant = 15.00 ms
  average S/N = 1.30; EN/IN = 5.29
fitting error: FID1 = 17.68%; FID2 = 47.38%
  param. of regular.: modeling
  permeability constant Cp = 7.00e-09
Site: Haddam Meadows, Site2
Loop: 4 - 37.5 Date: 17.11.2000 Time: 11:10

NUMIS data set:
C:\mol\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HIM2.inp
matrix:
C:\mol\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination = 72 degr, magnitude = 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 2.14; EN/IN = 2.79
fitting error: FID1 = 13.94%; FID2 = 26.43%
param. of regular.: E,T2* = 549.3; T1* = 4.530
permeability constant Cp = 7.00e-09
Site: Haddam Meadows, Site 3  
Loop: 4 - 37.5  Date: 17.11.2000  Time: 14:15

NUMIS data set:  
C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\Haddam_Meadows-2000.HM3.inp

matrix:  
C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\MATRIX\Had_mead-8sq.mmm

loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 6.48; EN/IN = 1.57
fitting error: FID1 = 6.71%; FID2 = 34.53 %
param. of regular: modeling
permeability constant C_p = 7.00e-09
Site: Haddam Meadows, Over boreholes, site4
Loop: 4 - 37.5  Date: 18.11.2000  Time: 09:10

NUMIS data set:
C:\moji\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM4.inp
matrix:
C:\moji\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 1.14; EN/IN = 1.75
fitting error: FID1 = 31.37%; FID2 = 32.04 %
param. of regular.: modeling
permeability constant Cp = 7.00e-09
Site: Haddam Meadows, Site 5
Loop: 4 - 37.5 Date: 18.11.2000 Time: 10:37

NUMIS data set:
C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\Haddam_Meadows-2000\HM5.inp
matrix:
C:\moi\REPORTS\usa2002\interp\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 0.95; EN/IN = 2.22
fitting error: FID1 = 22.40%; FID2 = 44.64%
param. of regular.: E,T2* = 1500.0; T1* = 10.000
permeability constant Cm = 7.00e-09
Site: Haddam Meadows, Site 6
Loop: 4 - 37.5 Date: 18.11.2000 Time: 11:52

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM6.inp

data matrix:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm

loop: eight square, side = 37.5 m

gemagnetic field:
inclination = 72 deg, magnitude = 53399.06 nT
filtering window = 198.7 ms

time constant = 15.00 ms

average S/N = 1.37; EN/IN = 3.00

fitting error: FID1 = 35.49%; FID2 = 26.75%

param. of regular.: E,T2* = 2500.0; T1* = 22.888

permeability constant $C_p = 7.00e-09$
Field tests of NUMIS\textsuperscript{plus} MRS equipment in USA

Site: haddam meadows profile, sounding 7
Loop: 4 - 37.5   Date: 18.11.2000   Time: 13:13

NUMIS data set:
C:\mo\REPORTS\usa2002\interp\Haddam_Meadows\Haddam_Meadows-2000\HM7.inp
matrix:
C:\mo\REPORTS\usa2002\interp\Haddam_Meadows\MATRIX\Had_mead-8sq.mmm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination = 72 degr, magnitude = 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 2.89; EN/IN = 1.46
fitting error: FID1 = 17.06\%, FID2 = 34.19\%
param. of regular.: modeling
permeability constant $C_p = 7.00 \times 10^{-9}$
Site: Haddam Meadows, site 8
Loop: 4 - 37.5  Date: 19.11.2000  Time: 09:49

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM8.inp
matrix:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 5.25; EN/I/N = 1.68
fitting error: FID1 = 7.16%; FID2 = 13.38%
param. of regular: E,T2* = 300.0; T1* = 12.875
permeability constant  Cп = 7.00e-09
Field tests of NUMIS® MRS equipment in USA

Site: haddam meadows, site 9
Loop: 4 - 37.5  Date: 19.11.2000  Time: 12:12

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM9.inp
matrix:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mrm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination = 72 degr, magnitude = 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 3.69; EN/IN = 1.12
fitting error: FID1 = 12.10%; FID2 = 31.90 %
param. of regular: modeling
permeability constant Cp = 7.00e-09
Site: Haddam Meadows, Site 10
Loop: 4 - 37.5  Date: 19.11.2000  Time: 14:09

NUMIS data set:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\Haddam_Meadows-2000\HM10.inp
matrix:
C:\moi\REPORTS\usa2002\interpr\Haddam_Meadows\MATRIX\Had_mead-8sq.mmm
loop: eight square, side = 37.5 m
geomagnetic field:
inclination= 72 degr, magnitude= 53399.06 nT
filtering window = 198.7 ms
time constant = 15.00 ms
average S/N = 5.92; EN/IN = 1.92
fitting error: FID1 = 7.93%; FID2 = 28.01 %
param. of regular.: modeling
permeability constant  Cp = 7.00e-09