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# 2D magnetic resonance tomography applied to karstic conduit imaging

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## Abstract

Karstic conduits play a crucial role for water supply in many parts of the world. However, the imaging of such targets is generally a difficult task for most geophysical methods. Magnetic Resonance Sounding (MRS) is a geophysical method designed for imaging of water bearing structures. Initially, MRS was developed for characterizing horizontally stratified aquifers. However, when applying a 1D MRS measuring setup to the imaging of 2D–3D targets, the size of which may be much smaller than the loop, the accuracy and the lateral resolution may not be sufficient. We have studied the possibility of simultaneously processing several MRS aligned along a profile to perform a Magnetic Resonance Tomography (MRT). This work emphasizes the gain of resolution for 2D–3D imagery of MRT versus the interpolation of 1D inversion results of MRS along the same profile. Numerical modelling results show that the MRT response is sensitive to the size and location of the 2D target in the subsurface. Sensitivity studies reveal that by using the coincident transmitting/receiving (TX/RX) setup and shifting the loop around the anomaly area, the depth, section and position of a single karstic conduit with a size smaller than the MRS loop size can be resolved. The accuracy of the results depends on the noise level and signal level, the latter parameter being linked to the depth and volume of the karstic conduit and the water content in the limestone matrix. It was shown that when applying MRT to the localization of 2D anomalies such as karstic conduits, the inclination of the geomagnetic field, the orientation of the MRT profile and the angle of crossover of the conduit by the MRT profile must be taken into account. Otherwise additional errors in interpretation should be expected. A 2D inversion scheme was developed and tested. Both numerical and experimental results confirm the efficiency of the developed approach.

*Keywords:* MRS; MRT; SNMR; PMR; Magnetic resonance sounding; Magnetic resonance tomography; Surface nuclear magnetic resonance; Proton magnetic resonance; Karstic conduit; Groundwater

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## 1. Introduction

Magnetic Resonance Sounding (MRS) is a geophysical method designed for imaging and quantitative description of water-bearing structures. It is based on the phenomenon of hydrogen proton magnetic resonance. In the subsurface, hydrogen is generally only present in water molecules and, consequently, the MRS signal is specifically linked with groundwater.

Initially, MRS was developed for characterizing horizontally stratified aquifers and has been used worldwide for more than 15 years. MRS is also used to describe the

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lateral hydrological variation across a watershed. For that purpose, MRS results in vertical logs are interpolated from sounding to sounding to provide a cross-section. The efficiency of 1D (one dimensional) profiling for imaging anomalies whose size is comparable to the loop size has already been studied by Warsa et al. (2002) and Legchenko et al. (2006). However, when applying this approach to the imaging of 2D–3D targets, the size of which may be much smaller than the loop (25 to 150 m diameter), the lateral resolution may be not sufficient.

Karstic conduits play a crucial role for water supply in many parts in the world. However, the imaging of such targets is generally a difficult task for most geophysical methods. A karst network develops in limestone by dissolution. The variability of karsts encountered in nature is so vast that each system is considered as unique: from thin and flat conduits developed at the top of an impermeable layer to large galleries, several tens of metres high and wide. If a drill-hole hits the conduit it can provide a huge water flow. However, since the hydraulic conductivity of the surrounding limestone matrix is several orders of magnitude less than the conduit itself, missing the karst conduit means that the borehole fails. Hence, high accuracy is needed to locate the drill site.

It has been shown that, if the conduit is big enough and full of water, standard 1D processing of MRS allows unambiguous detection of such targets (Vouillamoz et al., 2003). However, lack of lateral resolution is the limiting factor for siting a borehole using MRS results. To improve MRS efficiency, we propose carrying out a simultaneous inversion of several MRS measurements along a profile. We propose to introduce the terminology of Magnetic Resonance Tomography (MRT) when several MRS are processed simultaneously. The gain in resolution with MRT can be increased by using smaller distances between two soundings: a constant larger step can be used along the whole profile and can be reduced around the detected anomaly (down to one tenth of the loop diameter). Please note that we consider only the case where the same loop is used as transmitting and receiving antenna (coincident TX/RX loop setup).

We focused our numerical study on the response from 2D water-filled cavities with a section smaller than the loop size. Based on the modelling results, we propose a 2D inversion scheme specifically designed for prospecting water-filled conduits, and for detecting and estimating their size and location.

## 2. Background

A detailed explanation of the method can be found in previous papers (Weichmann et al., 2000; Legchenko and Valla, 2002). An enhanced model has recently been proposed (Legchenko, 2004) to consider the effect of time-varying drift of the geomagnetic field during measurements, especially in the presence of shallow water.

In thermal equilibrium, groundwater has a macroscopic spin magnetization vector aligned along the geomagnetic field. In MRS, a quasi-static and homogeneous geomagnetic field is assumed at the loop scale. An exciting magnetic field is generated by a pulse of oscillating current in the transmitting loop with a specific frequency (the Larmor frequency). The duration ($\tau$) and intensity ($I_0$) of the pulse both characterize the pulse moment $q = I_0 \cdot \tau$ (A ms).

In MRS, only the component of the exciting field perpendicular to the geomagnetic field contributes to tilting the spin magnetization vectors away from the equilibrium direction. The amplitude of this effective field is proportional to the current amplitude. According to Bloch's equations, the MRS signal reaches its maximum when the tilt angle between the magnetization vector and the geomagnetic field is 90° (Slichter, 1996). The signal (Eq. (1)) is recorded in the loop after the power is turned off and is characterized by its initial amplitude $E_0$ (nV), decay time $T_2^*$ ($s$), phase $\varphi_0$ (rad) and pulsation $\omega_0$ (rad/s).

$$\begin{aligned}\mathrm{signal}(q,t) &= E_0(q)\cos\,(\omega_0 \cdot t + \varphi_0(q))\exp(-\frac{t}{T_2^{*\mathrm{app}}(q)}) + \mathrm{Noise}(t) \quad (1)\\ &= \int_V w(r).K_{3D}(q,r)\exp(-\frac{t}{T_2^*(r)}) \cdot dr^3 + \mathrm{Noise}(t)\end{aligned}$$

$W(r)$ and $T_2^*(r)$ are respectively the water content $w(r)$ and decay time distributions in the ground, and $r = r(x,y,z)$ the coordinate vector. The kernel function $K_{3\mathrm{D}}(q,r)$ is the response of a unit volume $\mathrm{dr}^3$ at position $r$ in the ground:

$$K_{3D}(q,r) = \frac{\omega_0}{I_0} B_1(r) e^{i\varphi_0(r)} M_\perp(q,r) \quad (2)$$

$B_1(r)$ is the transmitted magnetic field component perpendicular to the geomagnetic field, and $M_\perp(q,r)$ is the transverse component of the spin magnetization for pulse $q$, which creates an alternating magnetic field measured after the pulse cut-off. The phase shift $\varphi_0(r)$ relative to the current in the loop is due to the electrical resistivity of the ground, the pulse shape, and the frequency shift between the Larmor frequency and the pulse frequency (Legchenko, 2004). As shown in Eq. (1), the MRS response is integrative. The responses from all water molecules below the loop (25 to 150 m diameter) are added together. The apparent decay time $T_2^*(q)$ is defined by fitting the recorded signal to a single