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Multi-channel surface NMR instrumentation and software for 1D/2D groundwater investigations

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ABSTRACT

Multi-channel surface nuclear magnetic resonance (NMR) instrumentation and software, developed in the United States, has been applied to investigate 1D and 2D hydrology at various locations in the Western US. The GeoMRI instrument offers several practical improvements over the previous state of the art in surface NMR instrumentation, including a multi-channel transmit/receive capability, a significantly shorter measurement dead-time of 10 ms, and an ultra-low receiver input noise density of less than 0.4 nV/sqrt (Hz). Two multi-channel NMR processing techniques, reference coil-based noise cancellation and integrated FID imaging, are shown to increase effective signal to noise ratios by an order of magnitude or more. These effective SNR gains enable multi-coil surface NMR to produce useful and reliable images when the post-averaged SNR is less than 1. We also suggest an alternate approach to imaging, in which NMR signals are initially isolated in the space domain, and then NMR parameter estimation is applied in the time domain. Experimental results are presented for recent surface NMR groundwater investigations conducted in Nebraska and Texas, USA.

1. Introduction

Single-channel surface NMR instruments have been commercially available for about 10 years. To date, their widespread use in hydrogeological investigations has been limited by their susceptibility to environmental and cultural noise, and their limitation to groundwater profiling in a single dimension: depth.

Susceptibility to noise continues to pose the primary obstacle to the widespread use of surface NMR for hydrological investigations (Legchenko, 2006). Notch filtering, aimed at zeroing the response to 50 Hz or 60 Hz power transmission harmonics, is the most common method of reducing noise in surface NMR measurements (Legchenko and Valla, 2003). A recent experimental study by Legchenko (2006) indicated that narrowband 50 Hz power harmonics represent only 20% to 50% of the total noise energy in a typical band-limited surface NMR measurement, while broadband non-stationary noise processes typically constitute a majority of the noise energy. Notch filtering may also distort the underlying NMR signal when the Larmor frequency is close to a multiple of 50 Hz or 60 Hz. Other noise reduction techniques have been proposed for detecting and removing impulse-like noise processes from surface NMR data (Li et al., 2006, Strehl et al., 2006). It makes sense to remove high-amplitude impulse noise artifacts from NMR data. When the density of impulse noise artifacts is high, removal of entire data records can increase the data collection time significantly, possibly by several integer factors. Removing only the affected portion of each data record will distort the underlying NMR signal unless more sophisticated processing is employed to reconstruct the lost portion of the desired NMR signal.

The use of a "figure-8" shaped surface coil is a simple and commonly employed form of spatial noise mitigation, and is often effective when the noise field is homogeneous across the coil surface. The "figure-8" coil shape alters the transmitted field pattern however, and significantly reduces the maximum depth of investigation compared to a circular or square surface coil. A modification to this method is the use of a displaced reference coil with reverse polarity, wired in parallel to the detection coil, with a passive diode-based switch to prevent current from flowing through it during the transmit pulse (Lange et al., 2006). This single-channel configuration acts as a conventional coil during transmit (for maximum depth of penetration) and acts like a figure-8 coil in receive mode, canceling the magnetic flux common to both coils. The modified figure-8 loop exhibits lower sensitivity to signals at larger depths in receive mode. Both the standard and modified configurations of the figure-8 loop operate by canceling the magnetic flux common to both coils. Their effectiveness depends on the homogeneity of the magnetic noise process across the coils. Such homogeneity is often limited in the vicinity of human development, and in situations with multiple competing noise sources (power line harmonics, electric fences, sferics, etc…).

Multi-channel surface NMR instrumentation enables the use of multiple, independent reference coils for space-based noise mitigation. The potential advantages of spatial or space/time processing

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include: no distortion of the underlying NMR signal (subject to proper placement of reference coils) and no requirement for noise process models. The use of separate receive channels for reference coils preserves all the spatial noise cancellation advantages of the figure-8 and modified figure-8 methods, and provides the additional degrees of freedom necessary to mitigate a plurality of interfering EM noise processes with differing temporal/spatial characteristics in a time/space inhomogeneous noise environment through adaptive signal processing (Haykin, 1996).

The development of multi-channel surface NMR instrumentation also facilitates time- and energy-efficient 2D and 3D groundwater imaging methods. Preliminary computer modeling by Hertrich and Yaramanci (2003) indicated that 2D surface NMR imaging with separated transmitter and receiver loops is feasible, and yields improved spatial resolution compared to 2D imaging with a single coincident transmit/receive loop processed over multiple displaced stations. Hertrich et al. (2005) conducted a 2D surface NMR field survey using a single-channel surface NMR instrument, by repeated soundings using all possible permutations of 4 transmit/receive coil locations (i.e. 16 separate soundings to generate a four-coil transmit/receive array data set), and concluded that multi-channel surface NMR instrumentation would enable superior 2D investigations at feasible survey speeds (Hertrich and Yaramanci, 2006).

The feasibility of 3D surface NMR groundwater investigations was investigated and demonstrated by Walsh (2006). Computer modeling demonstrated the ability to resolve a 3D target using an array of four circular surface coils laid out in a square pattern on the surface (approximate 10% overlap between adjacent coils). The feasibility of 3D surface NMR imaging was experimentally validated though laboratory surface NMR imaging experiments, conducted in the boosted B_0 field of an 8 ft×8 ft×4 ft Helmholtz coil (Walsh, 2006). In these experiments a rectangular container of mineral oil was imaged in three dimensions using an array of four small (43 cm diameter) multiple-turn surface coils, with resulting spatial resolution similar to the respective computer modeling (Walsh, 2006).

In this work, we describe the development of multi-channel surface NMR instrumentation and software, and their application to noise reduction and 2D NMR groundwater imaging. The GeoMRI instrument and the multi-channel surface NMR applications described herein were developed by Vista Clara Inc. over the past 4 years, with funding from the US National Science Foundation. The author was the principal investigator on the instrument development effort, but other employees, consultants and subcontractors played key roles in the development effort.

In this paper we outline the technical specifications and capabilities of the GeoMRI instrument. We demonstrate effective reduction of environmental noise using reference coils with adaptive signal processing. We introduce an integrated FID imaging method, which is useful for groundwater NMR imaging when the post-averaged signal to noise ratio (SNR) is less than 1. Finally, we present the results of some recent 1D and 2D groundwater investigations conducted in the United States.

2. Methods

2.1. Instrumentation

The field studies described in this paper were performed using the "GeoMRI" surface NMR instrument shown in Fig. 1. All power components are housed in one enclosed unit, which is installed in a small convertible cargo trailer. The GeoMRI instrument produces maximum AC current pulses in excess of 400 A, with a maximum of 4000 V across the coil terminals. The instrument has a DC bus capacitance of 0.24 F, which enables multiple-pulse sequences (e.g. spin-echo or 90–90) with minimal voltage and current drop between pulses. The surface coils are constructed of #8 AWG stranded tinned copper (approximate cross-section of 10 mm^2), with 15 kV DC insulation, high voltage Milspec environmental-rated connectors, in individual sections of 300 ft (91 m) length.

Fig. 1. GeoMRI, 4-channel surface NMR instrument (April 2006).

The GeoMRI instrument has a software selectable Tx/Rx dead-time of 10 ms or 15 ms, and is capable of measuring signals within 5 ms of the end of the transmit pulse. This shortened instrumentation dead-time provides for higher SNR and more accurate estimation of free induction decay (FID) properties (specifically initial amplitude and $T2^*$), especially for the shortest duration FID signals. The author is presently investigating the utility of shorter dead-times for the detection of silt-bound water, detection of water in magnetically permeable formations, and detection of capillary-bound water.

The GeoMRI system has 4 transmit/receive channels, allowing the system to transmit on one or multiple coils at the same time, and simultaneously receiving NMR data on up to four receive channels. The analog input circuitry has a bandwidth of approximately 10 kHz, and raw NMR data are directly digitized using 24-bit A/D's with zero time delay between channels. This broadband sampling approach preserves the broadband information content of the measured NMR signals, and the 24 dB dynamic range leaves plenty of headroom for the measurement of broadband noise and interference sources, which may be filtered out during post-processing as needed. Timing and phase jitter between successive measurements, and between channels, are negligible. The absolute phase offset of the input electronics has not been assessed, although it would be a straightforward procedure to calibrate any receiver-induced phase offset.

The receive electronics are designed to present a high impedance to each surface coil, to suppress mutual coupling between adjacent surface coils. An important aspect of this design is that the surface coils are not tuned in receive mode, as the use of parallel tuning capacitors would create low-impedance circuits enabling currents to flow freely through the coils in receive mode. Mutual coupling between surface coils, if not suppressed, will cause mixing of the signals amongst all coils in the receive array, and greatly complicate the problem of modeling and inverting NMR signal distributions in one or multiple dimensions. The absence of tuning capacitors in receive mode also eliminates the gain and phase response ambiguities associated with tuned surface loops.

The receiver open-circuit input noise is 0.4 nV/sqrt (Hz) at 2 kHz. This noise figure was measured in a noisy laboratory environment with the measured coil terminals left open, and the instrument powered on and transmitting through a coil connected to an adjacent Tx/Rx channel. Hence, this noise measurement includes the accumulated effects of all instrumentation and digitization noise. This ultra-