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Full Envelope Inversion of Surface-NMR Data for Retrieval of Hydro-geophysical Characterization

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ABSTRACT
In contrast to other geophysical approaches which only provide information on the lithological characteristics of aquifers indirectly, the surface-NMR technique yields hydro-geophysical parameters such as water content and relaxation time. In surface-NMR inversion process, from data space point of view, two inversion techniques (i.e., initial amplitude inversion (IAI) and time step inversion (TSI)) exist. In IAI, the initial amplitudes derived from free inductions decays are used to estimate water content. In TSI, the data set transferred into a water-content domain followed by mono-exponential fitting to the water-content domain to both estimate water content and relaxation time as a function of depth. Both methods take advantage of sub-data sets instead of the full data. In this paper, a novel inversion algorithm based on the application of the full decay cube, including the entire times and pulse moments, to determine simultaneously water content and relaxation time using mono-or multi-exponential behavior, is developed. To verify and compare the functionality of the inversion algorithms, some numerical experiments using synthetic and real data set are provided. The numerical results reveal that the comprehensive inversion algorithm outperforms IAI in terms of stability and resolution properties. The results indicated that using full data set yields improved stability and depth resolution compared to those of sub-data set.
Keywords: Surface-NMR, Hydro-geophysics, Parameter estimation, Non-linear inversion

INTRODUCTION
Surface-NMR as a non-invasive geophysical method provides direct information about the presence and hydro-geological properties of water-bearing layers. The field measurements includes energizing the subsurface by transmitting an alternative EM pulse through a surface antenna (coil) in order to generate a measureable exponentially decaying NMR signal at a depth that originates from the immersion of hydrogen nuclei in the Earth's magnetic field. Using inversion of NMR data a distribution of water content and relaxation time with respect to depth will be provided. This involves minimizing a cost function that is used to penalize undesirable model characteristics, such as penalizing models that do not closely reproduce the observed data. Based on model-space point of view, two algorithms including block and smooth inversion has been reported and from data-space perspective initial amplitude inversion (IAI) (Legchenko and Shushakov, 1998) and time step inversion (TSI) (Legchenko and Shushakov, 2002). Both methods take advantage of sub-data sets instead of the full data. In this study, it is aimed at proposing an inversion framework based on the comprehensive application of the decay cube, including the entire times and pulse moments, to determine simultaneously water content and relaxation time using multi-exponential behavior. Then, the results are compared to those of IAI using synthetic and real data set.

METHODOLOGY
In general, for a 3D earth, the surface-NMR forward model is given as follows (Müller-Petke and Yaramanci, 2010).

$$S(q,t) = \int K(z,q) \int W(z,T_2^*) exp\ (t/T_2^*) dT_2^* dv \qquad (1)$$

Where S is the measured complex-valued surface-NMR signal, $K(z,q)$ indicates the physics of the forward problem in dependency on pulse moment $\mathbf{q}$ and depth z, T_2^* is apparent transverse relaxation time, and $W(z,T_2^*)$ shows the subsurface partial water content (PWC) distribution including multi-exponential NMR relaxation signals. Whereas in this study we consider inversion of one spatial dimension, equation 1 can be reduced to a 1D problem by pre-integrating over $\mathbf{x}$ and $\mathbf{y}$ directions.

In IAI inversion, assuming mono-exponential NMR relaxation behavior, the PWC distribution reduces to the water-content depth distribution at the decay-time depth distribution. As a result, based on the merely application of the initial values (S_0) as input data to the inversion process equation 1 at the time $t = 0$ simplifies to:

$$S_0 = S(q, t = 0) = \int K(z, q) W(z) dz \quad (2)$$

Contrary to IAI in which merely initial amplitudes are used, the application of the full data cube including the entire pulse moments and decay times results in the following forward problem:

$$S(q, t) = \int K(z, T_2^*, q, t) W(z, T_2^*) dT_2^* dz \quad (3)$$

The inversion process in the proposed algorithm includes the retrieval of the PWC distribution $W(z, T_2^*)$ by which two parameters the water content W and the relaxation time T_2^* in terms of the depth z will be calculated. Note that to solve equation 3 it is required to discretized parameters T_2^* and z.

NUMERICAL EXAMPLES

In this section the functionality of the proposed inversion algorithm is verified using a synthetic example and a real dataset recorded on a superficial aquifer by a multi-channel NMR instrument (GMR-Vista Clara). Note that the inversion process is implemented on rotated data derived from deleting phase information from complex NMR data. The full synthetic NMR data set is simulated using a 100-m-side-cirlce loop with the Earth's magnetic field intensity of 47500 nT at an inclination of 60^0 and a declination of 0°. In addition, Fig. 1 depicts the true hydro-geophysical parameters (i.e., water content and relaxation times) and resistivity distribution in dependency on depth. It can be seen that a five-layer earth including two superficial and deep aquifers are modeled. The synthetic data are contaminated with Gaussian noise at 30-nV standard deviation for both real and imaginary parts of the signal.

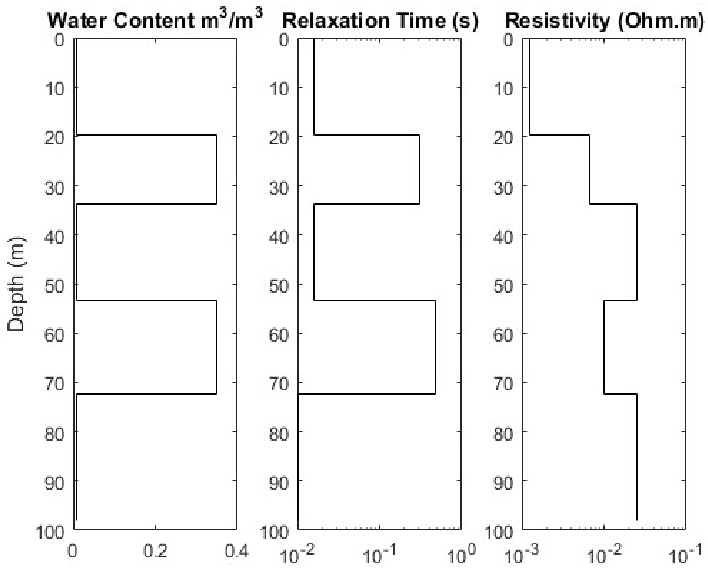

Figure 1. Synthetic five-layer model with different water content, relaxation time, and resistivity.

The results of implementing IAI algorithm and the inversion based on the full data set are represented in Fig. 2 and 3, respectively. Referring to Fig. 1 and 2, it can be observed that a better estimation of water content for the second aquifer is obtained by the proposed inversion scheme compared to IAI. This is due to the multi-exponential data fit during the inversion process.

Raw data before entering the inversion algorithm undergo processing including de-spiking, harmonic cancellation, envelope detection, stacking, and noise estimation (Ghanati et al, 2016). The field measurements were conducted with 50 m diameter circular loop that acted as coincident loop transmitter and receiver at the Schillerslage site, close to Hannover. The geomagnetic field was measured to be 49416 $\mathbf{nT}$ at $\mathbf{68}^{\circ}$ inclination. Fig. 4 and 5summarize the results of the application of IAI and the proposed inversion algorithm to a real data set, respectively. From Fig. 5, it is seen that the information obtained from a borehole located at the sounding corresponds reasonably closely with the resulting inverted parameters from the MRS measurements using the presented method.

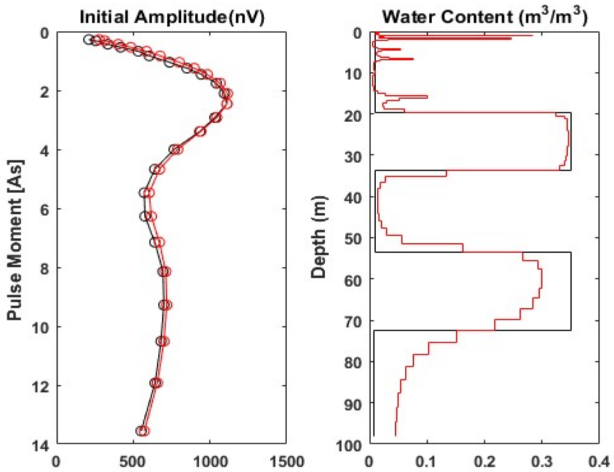

Fig. 2. Representation of IAI algorithm. Left: extracted initial values S_0 by mono-exponential fits to the rotated data with residual 6 nV. Right: estimated water content (red curve) and true model (black curve).

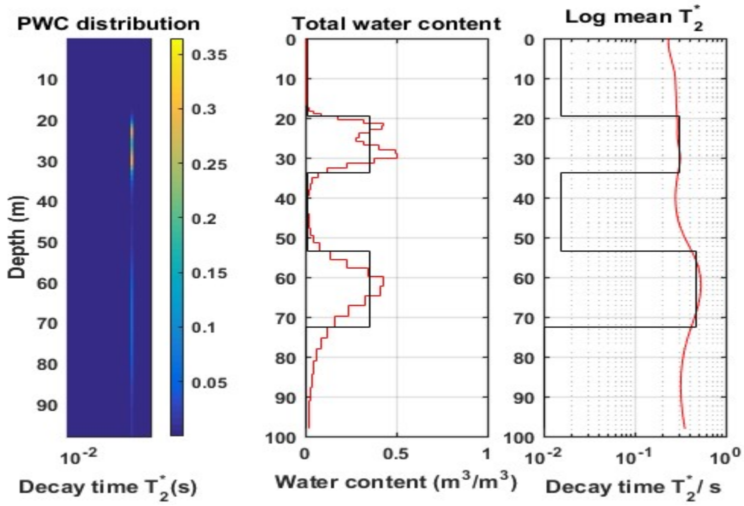

Fig. 3. Representation of the proposed algorithm. PWC distribution, total water content, and mean decay time depth distribution using rotated amplitudes dataset (left to right).

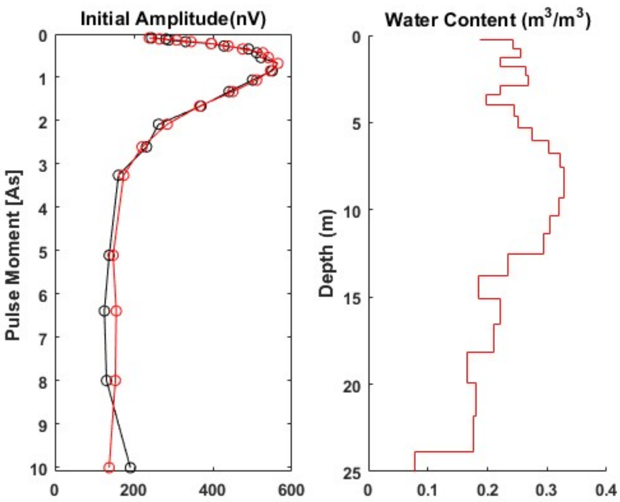

Fig. 4. IAI algorithm result of real data set. Left: extracted initial values S_0 by mono-exponential fits to the rotated data. Right: estimated water content (red curve).

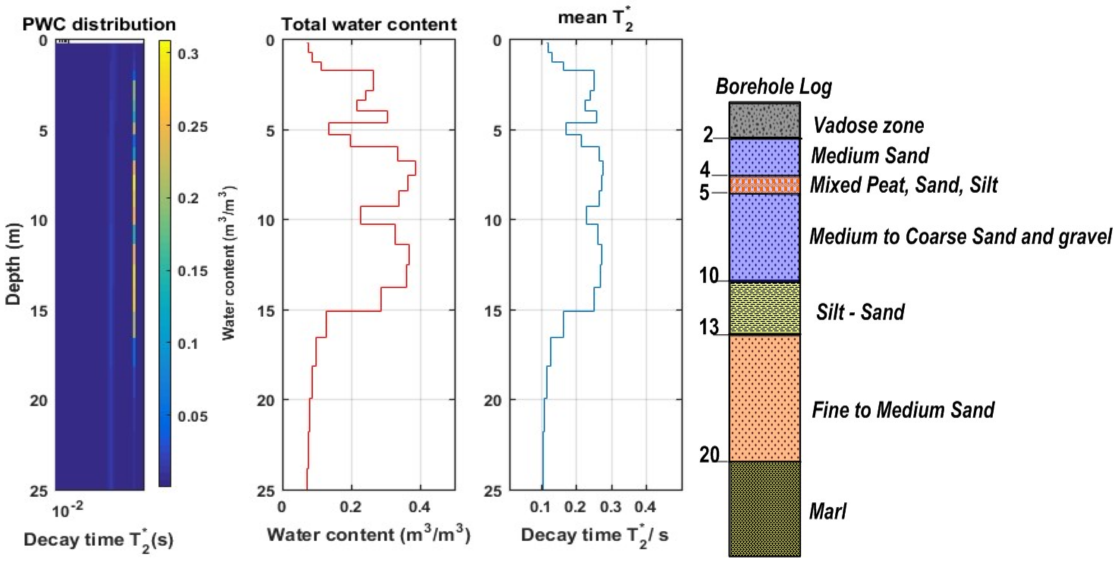

Fig. 5. The proposed inversion algorithm of real data set. PWC distribution, total water content, and mean decay time depth distribution using rotated amplitudes dataset (left to right). The water table measured in the borehole can be found at a depth of 2 m from the subsurface.

CONCLUSIONS

We presented a full envelope inversion framework based on the application of the entire surface-NMR data set to simultaneously invert water content and decay time using multi-exponential behaviour. We compared IAI and the proposed scheme using a simulated and field example. The results revealed that using full data set yields improved stability and depth resolution compared to the IAI algorithm.

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