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Earth's field NMR detection of oil under arctic ice–water suppression

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ABSTRACT

Earth's field NMR has been developed to detect oil trapped under or in Arctic sea-ice. A large challenge, addressed here, is the suppression of the water signal that dominates the oil signal. Selective suppression of water is based on relaxation time T_1 because of the negligible chemical shifts in the weak earth's magnetic field, making all proton signals overlap spectroscopically. The first approach is inversion-null recovery, modified for use with pre-polarization. The requirements for efficient inversion over a wide range of B_1 and subsequent adiabatic reorientation of the magnetization to align with the static field are stressed. The second method acquires FIDs at two durations of pre-polarization and cancels the water component of the signal after the data are acquired. While less elegant, this technique imposes no stringent requirements. Similar water suppression is found in simulations for the two methods. Oil detection in the presence of water is demonstrated experimentally with both techniques.

1. Introduction

We have developed earth's field NMR for detection of oil under or trapped inside Arctic sea-ice [1,2]. The device would be deployed by helicopter in case a leak or spill is suspected associated with oil production or transport. Two surface coils approximately 6 m in diameter, one for pre-polarization and one for transmit/receive, are stacked. The coils are large enough that their fields penetrate the ice of thickness 1–2 m.

One challenge is to detect the modest signal from perhaps a few hundred to several hundred liters of oil with a single-sided surface coil having a low filling factor at such a low Larmor frequency. We mitigate this challenge with a strong pre-polarization field B_p [3–11] of the order of 2.5 mT, approximately 50 times the strength of earth's magnetic field B_e ($\sim$50 μT), at a distance of about 1 m. Because the coil is so large, this requires approximately 12 kW during the pre-polarization process [12].

The second and larger challenge is to detect oil in the presence of a dominating water signal. A hypothetical 1 cm thick layer of oil under 1 m of ice will lie on top of an ocean of seawater. The sensitivity profile averages to an effective water depth of $\sim$2 m, meaning that the water signal will be 200 times larger than the oil signal. The ratio will be even larger if the amount of oil under the coil is less. Here we note that equal volumes of oil and water contain nearly equal numbers of hydrogen nuclear spins.

The chemical shift difference [13,14] between oil and water, $\sim$0.008 Hz (3.5 ppm) in the extremely weak magnetic field of the earth, is some 20 times smaller than the narrow line width of water and an even smaller fraction of the oil line width. Therefore, we rely on the large difference in the relaxation times of seawater with $T_1 = T_2 \sim 2$ s and oil with $T_1 = T_2 \lesssim 0.1$ s depending on oil composition and temperature, to selectively suppress the water signal.

To examine this problem another way, consider the difference in T_2 for these two materials. We take the T_2 ratio to be 20 and the intensity ratio to be 200. In the frequency domain, the line width ratio will be 20 and the ratio of areas under the peaks will be 200, implying that the water peak will be 4000 times as tall as the oil peak. Even at the half-width of the broader oil peak, the water signal will still be $\sim$20 times larger than the oil intensity at the same frequency, using Lorentzian line shapes for both oil and water.

In the time domain, the small oil component will show up as a small increment to the signal at the time origin of the FID. Because the FID amplitude at the time origin is proportional to the number of protons, the oil will contribute a very small portion, 0.5% in the example above, to the initial value of the FID (if issues of receiver recovery and probe ringing are ignored). We conclude that while the differences in T_2 or equivalently line width can provide some

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discrimination between oil and water, the desired suppression factor of at least 200 is larger than one could obtain from T_2 alone.

In ordinary NMR, diffusion [15] is another mechanism to differentiate oil from water. But we deem this to be impractical because of the need to apply a large magnetic field gradient with coils at least as large as the pre-polarization and transmit/receive coils. In addition, we may have to deal with relative motion of the water and the coils due to motion of the ice floe. For all of these reasons, water suppression based on the T_1 difference is essential and is the focus of this work.

2. Experiment

Most of the experiments reported here were performed in Albuquerque in a soccer field or a parking lot away from power lines. The pre-polarization coil was a multi-turn circular coil of 0.7 m diameter delivering a maximum magnetic field of ~15.3 mT with a 21 ms rise time. The current switch reduced the current to zero approximately 10 ms after the pulse [12]. The transmit/receive functions were performed with a 0.6 m diameter double-D gradiometer coil [1] as shown in Fig. 1, a variation of the figure-8 coil, stacked flat and centered on the pre-polarization coil. The double-D coil ideally has no net magnetic moment and is not sensitive to spatially uniform magnetic interference from distant sources.

Some experiments were performed on a pond near St. Johns Newfoundland, Canada. The 6 m diameter pre-polarization loop coil was laid on top of a double-D transmit/receive coil of the same size and consisted of 44 turns of a bundle of 30 paralleled conductors of #11 AWG aluminum magnet wire. The pre-polarization current used was 200 A and the field generated was approximately 2.5 mT with a rise time constant of ~125 ms. The pre-polarization used a simple multi-turn round flat coil weighing about 250 kg.

Spin simulations were performed to assess the performance of the water-suppression schemes. The simulations addressed how effectively the spin magnetization **M** follows the changing direction of the total field consisting of the earth's field plus the pre-polarization field. Even though earth's magnetic field is very uniform, the pre-polarization field is not; its magnitude and direction vary over a wide range depending on the position with respect to the coil. The fact that there is a wide range of directions in which the pre-polarization field is oriented means the spin magnetization **M** needs to rotate different amounts depending on its spatial position. This puts varying degrees of stress on the adiabaticity condition [13,14].

Most simulations did not include relaxation effects because the changes took place in times short compared to the shortest relaxation times considered. However, relaxation times were included in the calculations of the longitudinal component of magnetization M_z during inversion-recovery and double acquisition sequences, where relaxation during the field pulse is crucial.

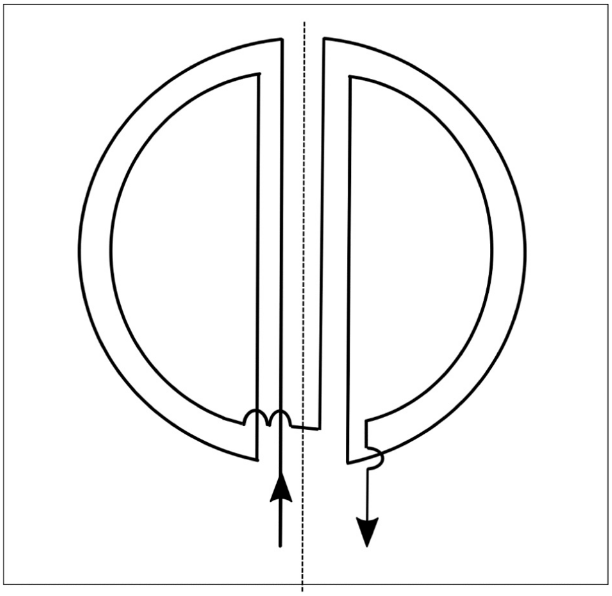

Fig. 1. Geometry of double-D coil, a design of zero net magnetic moment so it is insensitive to uniform interference signals. Only two turns in each half are shown. The coil can easily be folded along the dashed line.

3. Results

3.1. Inversion-recovery

The first water suppression method we considered was inversion-recovery nulling combined with selective saturation [1], *without* pre-polarization. The inversion nulling used an adiabatic sweep pulse (which was later found to be inadequate for large B_1, $B_1 \gtrsim B_e$, as discussed elsewhere [16]). The selective saturation of water was accomplished by simply repeating the inversion-nulling operation rapidly compared to the water T_1 to give the water protons little time to develop much longitudinal magnetization, further attenuating water's contribution to the signal [17]. This method had severe sensitivity issues due to the absence of pre-polarization (pre-polarization gave a X50 or greater signal boost).

3.2. IR-PP

We next adapted the inversion-recovery nulling procedure for the pre-polarization field as shown in Fig. 2a, called IR-PP. Because the pre-polarization field is not uniform, all inversion and excita-

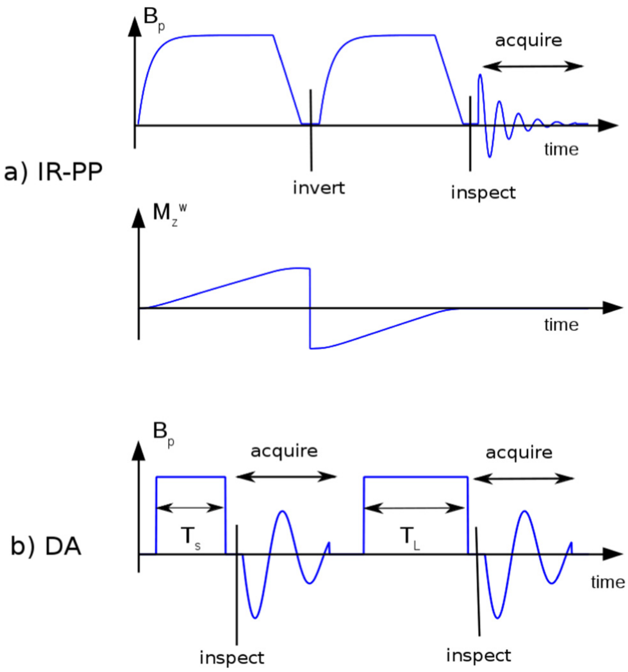

Fig. 2. Water suppression sequences relying on differences between the oil and water T_1. (a) Timing diagram of IR-PP sequence; the pre-polarization pulses are drawn and inversion and inspection pulses are marked. The water magnetization M_z^w is also shown. (b) Double acquisition sequence (DA) timing; the pre-polarization pulses are idealized as rectangular.