gradient-based Surface NMR for improved Detection and Resolution of Shallow Groundwater

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Surface NMR (sNMR) is a well-established geophysical method that allows non-invasive and direct detection of groundwater and measurement of aquifer properties to depths of up to 150m. This measurement is done at Earth’s geomagnetic field, using a surface loop of wire with large AC current pulse(s) to excite groundwater hydrogens, which generates a secondary alternating magnetic field which is detected as a voltage on the surface loop. Signal levels of typical sNMR measurements depend on the size of the receive coil and the amount of water in the subsurface, and typically vary between 10-1000nV. This typically very small signal level sometimes requires relatively long acquisition times and advanced noise reduction schemes to achieve a reasonable signal-to-noise ratio (SNR).

While sNMR has been adopted for coarse aquifer characterization, it has limited sensitivity and limited spatial resolution to resolve shallow subsurface parameters associated with many critical processes including contaminant transport, nutrient cycling, cryosphere thaw, and hydromechanical soil failure. For shallow groundwater investigations, sNMR can be performed using smaller coil setups for a more focused footprint (i.e. loop sizes on the order of 1-2 meters), but to obtain a robust SNR in a reasonable time the acquisition setup must also incorporate magnetization pre-polarization, adiabatic excitation pulses, or both. Although pre-polarization and adiabatic excitation are useful for increasing the signal amplitude in small-scale sNMR, neither of these methods are capable of improving spatial resolution of detected groundwater signal.

In this work we developed a novel sNMR method that adapts the standard imaging approach from medical MRI with a goal to enhance detection and resolution of shallow groundwater. Specifically, we use a second surface loop to generate a gradient field that is imposed on top of the static B0 field. This gradient is turned on for a short duration after excitation pulse to acquire a unique phase-encoding pattern across the subsurface volume. To analyze the gradient-based sNMR data we have developed an inversion algorithm that incorporates the phase-encoding gradient into the inversion kernel.

To validate this novel gradient-based sNMR approach, we first conducted a series of small-scale experiments using an outdoor pool filled with a known layer of water. We observed that a single adiabatic pulse in combination with pre-polarization and phase-encoding gradients is capable of significantly improving the detection and resolution of shallow water layer compared to conventional sNMR methods. Next, we conducted field tests using a medium scale experimental setup to detect and image ground water to depths of up to 20m, at two well characterized sites at Ebey Island, WA, and Larned, KS. We used high resolution direct-push NMR (DP NMR) to assess the accuracy of gradient-based sNMR results. Here, good correlation between DP NMR and sNMR results collected with adiabatic pulse and gradients was observed. At both sites, high-resolution gradient-based sNMR was able to identify three aquifer zones that were also identified in the DP NMR logs, where conventional sNMR methods were only able to resolve the two deeper aquifer zones. Finally, we demonstrated the ability of using imaging gradients in combination with non-adiabatic pre-polarization turn off to detect and spatially resolve shallow water without applying any transmit pulses.

The gradient-based imaging approach demonstrated here may be combined with tip angle-based imaging with no change to the structure of the underlying linear inversion formulation or approach. The gradient-based imaging approach is also independent of the pulse sequence, though its combination with adiabatic pulse excitation and pre-polarization with non-adiabatic shutoff enable complimentary gains in both sensitivity and resolution.