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Environmental Geophysics

Mike Hatch
Associate Editor for
Environmental Geophysics
michael.hatch@adelaide.edu.au

Welcome to *Preview* readers this month. In this column Dave Walsh, president of US-based Vista Clara Inc., introduces some new geophysical tools that Vista Clara (VC) have developed to measure water content in the very near surface. VC has been producing state-of-the-art geophysical tools that use nuclear magnetic resonance to detect water in the subsurface. The instruments that he is introducing here are unique in their ability to characterise the shallow unsaturated zone both for water content as well as for relative pore size, with minimal to no physical disturbance of the soils in the zone of investigation. This work was done in collaboration with Ken Hurst Williams from Lawrence Berkeley Laboratory (US DOE); their interest was to develop tools for monitoring carbon cycling in near surface soils.

Portable nuclear magnetic resonance tools for measuring and monitoring soil moisture

Dave Walsh
Vista Clara Inc.
davewalsh@vista-clara.com

Soil moisture content, and its distribution in space and how it changes in time, has a critical influence on processes in the natural world ranging from land surface evolution to ecosystem development, carbon cycling, climate variation, groundwater recharge and groundwater flow. There is a particular need for sensors that measure soil water content non-invasively. Invasive measurement techniques, like gravimetric measurement of soil samples, can cause significant disturbance of the sample under investigation and these disturbances can lead to significant errors when estimating volumetric water content. Other types of sensors that require electrical or physical contact with subsurface soil are also affected by other similar, difficult to quantify errors due, for example, to disturbance or displacement of soil during or after emplacement of the sensor. For example, when measuring soil moisture content within or beneath paved surfaces, invasive soil moisture measurement is either impractical, or causes unacceptable damage to the structure under investigation. Invasive sampling and/or measurement methods can also introduce artefacts, such as the creation of artificial paths for fluid migration, thereby confounding robust quantification of time-varying moisture dynamics. Non-invasive approaches avoid these effects entirely.

Nuclear magnetic resonance (NMR) is a non-invasive physical measurement that is widely used in medicine (Liang and Lauterbur 1999), oil and gas development (Kenyon et al. 1988), and more recently groundwater hydrology (Walsh 2008, Walsh et al. 2012, 2013). NMR measurements are based on the detection of the weak magnetic moment that is present in the hydrogen protons of each H_2O molecule. When placed in a static magnetic field B_0, the magnetic moments of individual hydrogen protons align weakly in the direction of the static field. This causes the water sample to exhibit a small magnetic moment. To detect the magnetic moment of the water, a perpendicular, alternating magnetic field B_1 is applied to the sample at a specific frequency, causing the individual proton magnetic moments to rotate in phase about the static field axis and tip away from the static field axis. When the alternating field B_1 is turned off, the magnetic moments from the hydrogen protons continue to rotate in phase about the static field axis, generating a circularly rotating magnetic moment that can be detected using a nearby induction coil. The detected NMR signal (or spin echo train) generally exhibits a multi-exponential decay in the time domain, and the signal magnitude and time constants derived from this signal are used to characterise water content in saturated and unsaturated soils. The initial signal amplitude is directly proportional to the total quantity of water – i.e. the total volumetric water content. The signal decay rate reflects the geometry of the pore environment, with fast-decaying NMR signals indicating water in small pores, and slow-decaying NMR signals indicating water in large pore sizes. As a practical matter, to accurately detect and measure water content in unsaturated soils, it is important that the NMR measurement is able to detect the fast decaying early time signals.

To meet the increasing demands for fast, accurate and high resolution measurement of soil moisture, we developed the modular Dart and Discus NMR soil moisture tools. This family of man-portable NMR instruments, shown in Figure 1, includes a battery powered NMR control unit, a small diameter in-situ NMR probe (‘Dart’), and a non-invasive NMR sensor that sits on the ground (‘Discus’). The NMR control unit includes a high speed data acquisition

Figure 1. *Portable nuclear magnetic resonance (NMR) soil moisture instruments. Left: 4.45cm diameter 'Dart' NMR soil moisture probe with control unit. Right: 'Discus' non-invasive NMR soil moisture profiling sensor.*

system and compact RF amplifier, and is powered by internally housed batteries. The Dart NMR probe is designed for measurements in small temporary soil core holes, up >30 m in depth (depending on cable length). The Dart probe has a diameter of 45 mm, and senses water content in two thin cylindrical shells at a distance of about 5 cm from the outer surface of the probe with a vertical resolution of 25 cm. The Discus sits on the ground, collecting data on water content at four distinct depth zones ranging from 5 cm to 20 cm. Both sensors collect NMR data with an echo spacing of less than 500 microseconds; fast enough to measure water content in almost all naturally occurring soil types. Typical measurement times for these tools range from 3 to 10 min per location. Figure 2 shows an example of data collected using the Dart, highlighting the raw data and some of the information available from the reading.

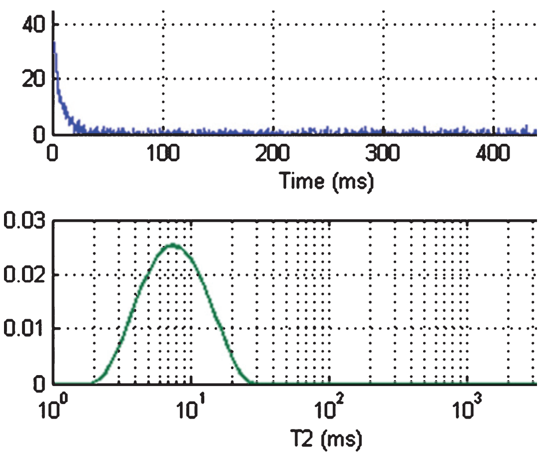

Figure 2. *Typical raw signal decay and multi-exponent fit for data collected in saturated fine grained sediments using the Dart system. Total water content is estimated at ~40%, while mobile water content is <0.1%.*

Since their commercial introduction in 2014, the Dart and Discus tools have been used by government and industry users for soil and shallow aquifer investigations in the US, Australia, Canada and Europe. A larger 1.0 m Discus sensor is presently under development, and will be capable of non-invasive soil moisture measurements to depths up to 0.5 m. A multi-coil Dart probe is also currently under development that is intended to be used for long-term, multi-level monitoring of soil moisture content.

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