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# Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons

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[1] Soil moisture content on a horizontal scale of hectometers and at depths of decimeters can be inferred from measurements of low-energy cosmic-ray neutrons that are generated within soil, moderated mainly by hydrogen atoms, and diffused back to the atmosphere. These neutrons are sensitive to water content changes, but largely insensitive to variations in soil chemistry, and their intensity above the surface is inversely correlated with hydrogen content of the soil. The measurement with a portable neutron detector placed a few meters above the ground takes minutes to hours, permitting high-resolution, long-term monitoring of undisturbed soil moisture conditions. The large footprint makes the method suitable for weather and short-term climate forecast initialization and for calibration of satellite sensors, and the measurement depth makes the probe ideal for studies of plant/soil interaction and atmosphere/soil exchange. **Citation:** Zreda, M., D. Desilets, T. P. A. Ferré, and R. L. Scott (2008), Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons, *Geophys. Res. Lett.*, *35*, L21402, doi:10.1029/2008GL035655.

## 1. Introduction

[2] Because of its long residence time [*Entekhabi et al.*, 1992; *Entin et al.*, 2000; *Wang et al.*, 2006], soil moisture moderates regional climate, much as the ocean does, making quantification of soil moisture crucial for weather and short-term climate forecasting [*Beljaars et al.*, 1996; *Dirmeyer*, 1999; *Koster and Suarez*, 2003]. But soil moisture measurements useful for atmospheric and land-surface applications are difficult to make. Point measurements must be scaled up to larger areas, but the inherent small-scale heterogeneities of soils make such upscaling difficult, although technically possible [*Famiglietti et al.*, 1999, 2008], and costly [*Western et al.*, 2002] due to the impracticality of collecting enough point measurements to support upscaling at a large number of sites. As a result, large-scale and long-term soil water data useful for atmospheric applications are practically impossible to obtain from point measurements. Large-scale satellite remote sensing methods have other limitations [*Entekhabi et al.*, 2004], including shallow measurement depth, limited capability to penetrate vegetation or snow, inability to measure soil ice, sensitivity to surface roughness, discontinuous temporal coverage and short life span of satellite missions.

[3] We present a novel non-invasive technique that utilizes the dependence of the low-energy cosmic-ray neutron intensity above the ground surface on the hydrogen content of soil. The cosmic-ray method is based on slowing down and thermalization of cosmic-ray neutrons by hydrogen atoms present in soil. Soil moisture greatly affects the rate at which fast neutrons are moderated, controlling neutron concentration in soils and prescribing their emission into the air. Dry soils have low moderating power and are therefore highly emissive; wet soils are more moderating and therefore less emissive as highly moderated neutrons are more efficiently removed from the system. The change in soil neutron emission is sufficient to produce a clear signal in the neutron intensity above the surface. For soil moisture content varying from zero to 40% volumetrically, the corresponding decrease in cosmic-ray neutron intensity above the surface is 60%, a hundredth of which can easily be measured using a neutron detector.

## 2. Cosmic-Ray Neutrons on Earth

[4] Interactions of cosmic rays with nuclei produce almost all neutrons in the atmosphere [*Hess et al.*, 1959] and in the top 1 m of the crust [*Fabryka-Martin*, 1988]. Primary cosmic rays, mostly protons, collide with atmospheric nuclei and create cascades of secondary neutrons [*Desilets and Zreda*, 2001, Figure 1] that can penetrate the atmosphere, collide with nuclei in soils, and produce fast neutrons with median energy of 1–2 MeV [*Hess et al.*, 1961].

[5] Neutron intensity in the subsurface is controlled by the scattering and absorption properties of soil elements. The two most important scattering properties are the macroscopic elastic scattering cross section, $\Sigma(\mathrm{N} \cdot \sigma_{\mathrm{sc}})$, where N is the number of atoms and $\sigma_{\mathrm{sc}}$ is the elemental scattering cross section (the probability that a neutron will collide with the nucleus in such a way that momentum is conserved), and the average logarithmic energy decrement per collision, $\xi$, which is the energy lost by the neutron through elastic collisions (inversely proportional to the atomic mass of the nucleus [*Bethe et al.*, 1940]). The absorption of neutrons is described by the macroscopic absorption cross section, $\Sigma(\mathrm{N} \cdot \sigma_{\mathrm{a}})$, where $\sigma_{\mathrm{a}}$ is the cross section for an element.

[6] At energies above a few eV, the neutron flux at a given energy (E) depends on the rate at which neutrons are scattered down to lower energies. In this case, the subsurface equilibrium neutron intensity is [*Glasstone and Edlund*, 1952] $\mathrm{Q} \cdot (\mathrm{E} \cdot \Sigma(\mathrm{N} \cdot \sigma_{\mathrm{sc}} \cdot \xi))^{-1}$, where Q is the neutron source intensity (proportional to the intensity of incoming energetic cosmic rays), $\sigma_{\mathrm{sc}} \cdot \xi$ is the moderating power of an element, and $\Sigma(\mathrm{N} \cdot \sigma_{\mathrm{sc}} \cdot \xi)$ is the macroscopic

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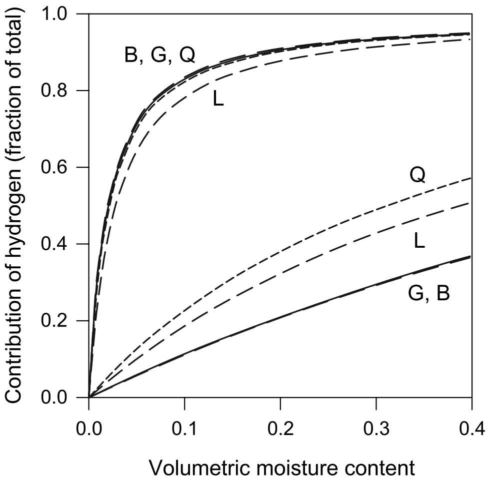

**Figure 1.** Contribution of hydrogen to the slowing-down power of the medium (upper series) and to the total macroscopic absorption cross-section (lower series) for soils derived from four rock types: basalt (B); granite (G); quartzite (Q); and limestone (L).

slowing down power of a material. A greater slowing down power means that neutrons are more effectively moderated, which makes the neutron intensity lower. In practice, because of the combination of high slowing down power of hydrogen (the product $\sigma_{sc} \cdot \xi$) and its prevalence in natural soils, the slowing down power of a soil is dominated by the hydrogen contained in water (Figure 1 and Data Set S1 in the auxiliary material[1]). Consequently, the intensity of low-energy neutrons above the surface shows a strong inverse correlation with the hydrogen content of the soil.

## 3. Using Cosmic-Ray Neutrons to Measure Soil Moisture

[7] Theoretical calculations [*Bethe et al.*, 1940] and observations [*Hendrick and Edge*, 1966] suggest that the intensity of low-energy (1 keV) neutrons depends on the hydrogen content of soil. Measurements of cosmic-ray neutrons in variably-saturated soils showed that neutron intensity and soil moisture content are inversely correlated [*Kodama et al.*, 1985], indicating the feasibility of invasive cosmic-ray neutron measurements. Because neutrons that are generated and moderated in the ground diffuse back into the air, this feasibility also applies in the case of non-invasive measurements above the ground surface.

### 3.1. Responses and Sensitivities to Soil Moisture and Chemistry

[8] Neutron intensity above the surface is inversely correlated with soil moisture (Figure 2). The shape of the response function for fast and epithermal neutrons is related to the contribution of hydrogen to the moderating power, and for thermal neutrons to the macroscopic absorption cross-section and moderating power (Figure 1). Thermal neutrons have a different sensitivity to varying soil moisture content than do fast and epithermal neutrons (Figure 2) because thermal neutron intensity also depends on chemical composition of the soil matrix and soil water. Elements with high neutron absorption cross sections, such as Ti, Gd and B, reduce the intensity of thermal neutrons, but not the intensity of fast and epithermal neutrons, as these elements contribute little to the moderating power of the medium (Data Set S1). Fast and epithermal neutrons have greater sensitivity to moisture content variations than thermal neutrons. In each energy region, both the neutron intensity (Figure 2) and the sensitivity decrease with increasing moisture content.

### 3.2. Footprint and Measurement Depth

[9] The lateral extent of the measurement volume (the region within which 86%, two e-fold drops or $1 - 1/e^2$, of the counted neutrons originate) is large (Figure 3, top) and the depth of measurement is shallow (Figure 3, bottom). A probe placed within a few meters of the soil surface has a footprint with a diameter $\sim$670 m at sea level (Figure 3, top). The footprint size does not depend on soil moisture content, but is inversely proportional to atmospheric pressure because in thinner air neutrons can travel farther. The measurement depth depends strongly on soil moisture,

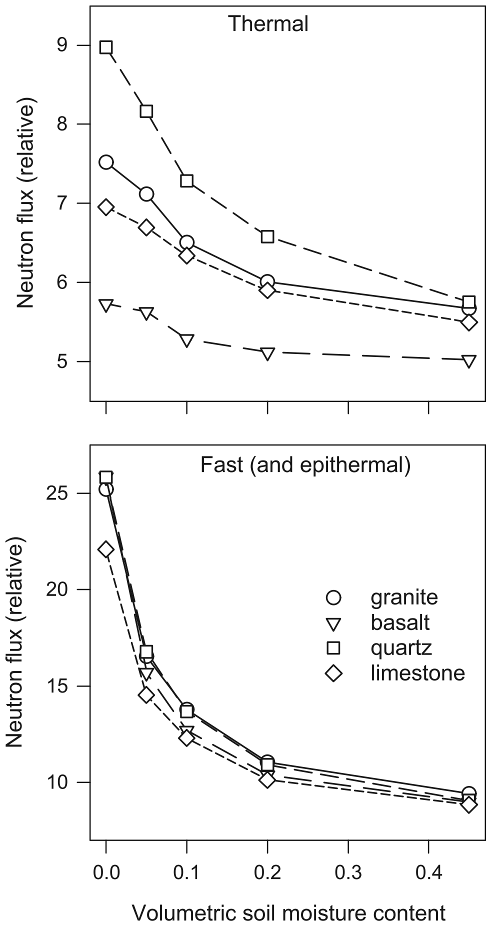

**Figure 2.** Responses of (top) thermal and (bottom) fast (and epithermal) neutron intensities above the surface to soil moisture changes for soils derived from four parent rocks: granite (circles), basalt (triangles), quartzite (squares) and limestone (diamonds). Calculated using the Monte Carlo N-Particle (MCNP) transport code [*Briesmeister*, 1997].

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[1] Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2008gl035655.

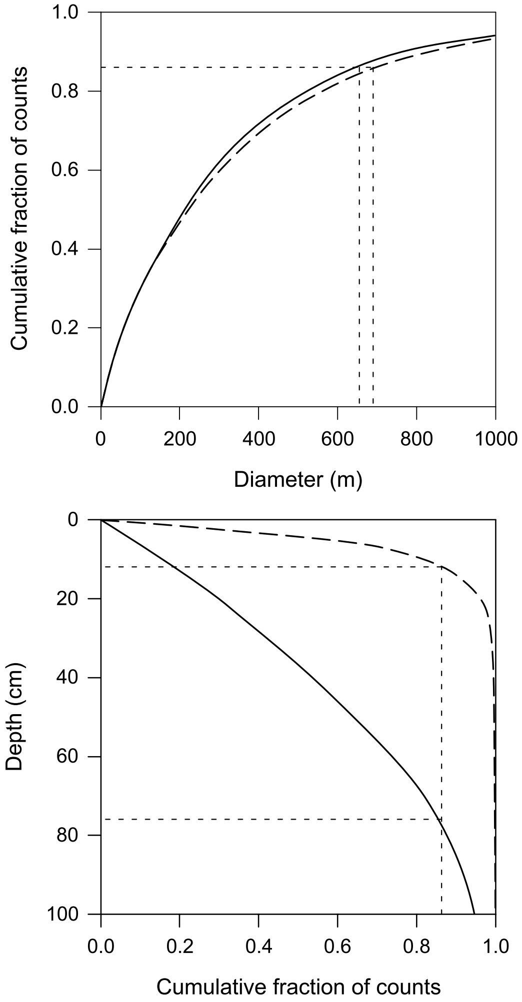

**Figure 3.** (top) Measurement area (footprint) and (bottom) depth of measurement of a fast (or epithermal) neutron detector placed at the surface. Solid lines are dry soil (0% moisture); dashed lines are saturated soils (40% water by volume); and short-dashed lines show 86% $(1 - 1/e^2)$ of the neutrons. Calculated using the MCNP code. Solid: silica sand, 100% $SiO_2$, 10 ppm B, 2 ppm Gd, particle density 2.65 g/cm$^2$, porosity 0.4, dry bulk density 1.6 g/cm$^2$. Air: 79% N, 20% O, 1% Ar. Pore water: 100% $H_2O$.

ranging from 0.76 m in dry soils to 0.12 m in wet soils (Figure 3, bottom), but it is independent of air pressure.

### 3.3. Calculation of Soil Moisture From Neutron Data

[10] Soil moisture is calculated from neutron count data using calibration functions similar to those in Figure 2. The shape of the calibration function is known from neutron transport simulations. The absolute neutron intensity varies with location due to variable soil chemistry, but variations are small at epithermal and fast energies (1 eV – $10^6$ eV) because neutron absorption is insignificant. The absolute intensity also changes with altitude and latitude, due respectively to the atmospheric and geomagnetic shielding of neutron-generating cosmic rays, but correction functions are known [*Desilets and Zreda*, 2003]. Thus, at least one independent measure of the average soil moisture content representative of the footprint is needed to calibrate the neutron counts to moisture content.

### 3.4. Measurement Uncertainty

[11] The analytical precision of neutron intensity measurements is governed by Poisonian statistics [*Knoll*, 2000], where for N counts the coefficient of variation is $N^{-0.5}$. A count rate at sea level using a small $^3$He proportional counter [*Knoll*, 2000] (590 cm$^3$ at 0.4 MPa) is approximately 2600 counts/hr, corresponding to a precision of 1.9% when counting for one hour. As the count rate increases with altitude, the precision improves. The precision can be improved by increasing integration time and by using multiple or larger detectors.

[12] The precision of neutron measurements is the main factor that determines the precision of soil moisture measurement. Because the calibration function is non-linear, achieving the same uncertainty requires longer integration times for wet soils than for dry soils. The calculated time needed to obtain a 2% uncertainty ranges from 0.1 hrs to 4 hrs for soils with moisture contents between 5% and 30%, respectively. (For comparison, the NASA's satellite microwave mission Soil Moisture Active and Passive (SMAP) will measure soil water content to 4%.) This result shows that the cosmic-ray method can give precise measurements of soil moisture content within a time scale relevant to atmospheric dynamics.

## 4. Field Applications

### 4.1. Continuous Monitoring of Soil Moisture

[13] A cosmic-ray soil moisture probe has been operated in a grassland of the San Pedro River valley, southeast of Tucson, Arizona, USA, since July 2007. Cosmic-ray neutron intensity was measured with a proportional counter filled with $^3$He [*Knoll*, 2000] (130 cm$^3$ at 1 MPa) and surrounded by 2.5 cm of low-density polyethylene to make the probe sensitive to fast neutrons, and mounted on a pole 1 m above the surface. In addition to neutron measurements, two sets of 48 gravimetric moisture determinations at depths of 0–25 cm each were obtained, one when the soil was dry (before the summer rains), the other when the soil was wet (after a month of summer rains). Two other sets of data were used for comparison: soil water contents from two sets of time-domain reflectometry (TDR) probes (CS616 from Campbell), and precipitation amounts from a rain gauge, both located within 20 m of the cosmic-ray probe (see *Scott et al.* [2006] for more information about the site). Soil moisture contents derived from cosmic-ray measurements show an inverse correlation with precipitation, as expected, and agree with average moisture contents from gravimetric soil samples taken within the footprint (Figure 4). Furthermore, the temporal patterns of wetting and drying inferred from TDR and cosmic-ray data are nearly identical, despite their different measurement volumes (point measurement with TDRs, and areal average with cosmic-ray probe). This agreement shows that the cosmic-ray probe can reliably track soil moisture changes and demonstrates the feasibility of the non-invasive cosmic-ray soil moisture method.

### 4.2. Other Potential Applications

[14] Whereas measuring soil moisture content is the primary application for which the cosmic-ray neutron probe

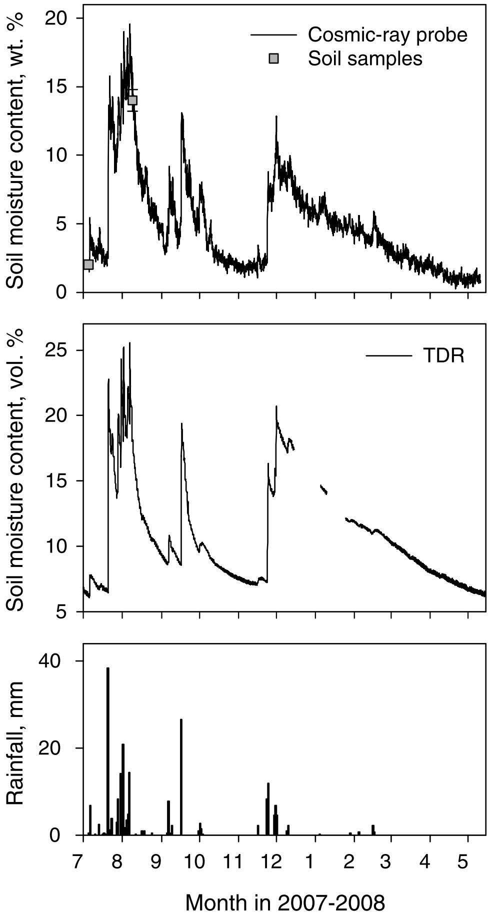

**Figure 4.** (top) Hourly soil moisture content measured with the cosmic-ray probe, and calibration points averaged from 48 gravimetric samples collected within the footprint. (middle) Average hourly soil water content from TDR measurements from two 30 cm deep profiles within 20 m of the cosmic-ray probe. (bottom) Daily precipitation from a rain gauge located within 20 m of the cosmic-ray probe. The data sets for Figure 4 are in Data Sets S2–S4.

has been developed, other potential applications exist. The probe also responds to any water above the ground surface, such as snow pack and ponded water, water in the canopy and other biomass [*Desilets et al.*, 2007], and water intercepted by the canopy. This hydrogen-rich layer disturbs the air/ground equilibrium profiles of cosmic-ray neutrons and results in either decreased or increased intensity of low-energy neutrons, depending on the neutron energy and the amount and distribution of the additional water. The presence of this hydrogen is a potential complication in the measurement of soil moisture because the cosmic-ray neutron signal integrates two variables. But because neutron intensity variations are predictable from theory, their proper analysis can be used to determine the amount of water above the ground surface in addition to soil moisture (D. Desilets et al., manuscript in preparation, 2008). Two or more sources of water above the detector are not distinguishable with neutrons alone, but with additional information their separation is possible. For example, canopy water and intercepted water, which are colocated and thus cannot be discerned using cosmic-ray neutrons alone, can be distinguished on the basis of their dynamics: whereas canopy water changes slowly, intercepted water changes rapidly.

## 5. Summary and Conclusions

[15] The cosmic-ray soil moisture probe has many useful features: it measures soil moisture at an intermediate scale of hundreds of meters with minimal dependence on soil type; it is non-invasive and non-contact; it does not contain a radioactive source; it can be automated easily, consumes little energy, and is compatible with low data stream telemetry techniques. The cosmic-ray neutron probe can be used jointly with other techniques, thus bridging the gap between point measurements and airborne or satellite imaging.

[16] The unique features of the cosmic-ray neutron probe make it ideal for providing measurements with the precision necessary and the appropriate scale for meteorological [*GLACE Team*, 2004] and intermediate- to large-scale hydrological [*Ferranti and Viterbo*, 2006] and ecological [*Rodriguez-Iturbe and Porporato*, 2004] applications. In addition, we see many potential applications not hitherto possible with existing techniques, such as measuring snow pack averaged over tens of hectares; assessing permafrost melting; measuring canopy water storage and biomass changes; monitoring irrigated root-water status; and monitoring weight of snow on rooftops. Future work will focus on improved analysis of the neutron intensity time series, analysis of complex signals due to combined effects of moisture in the soil and above the ground surface and due to heterogeneity of soil moisture, and the simultaneous use of multiple probes to extract more information from the measurements. With better understanding of cosmic-ray neutrons in and above the surface, the cosmic-ray method will improve the way of monitoring near-surface water, which will harbinger changes in the assessment of the role of water in the natural environment.

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