Footprint Characteristics of Cosmic-Ray Neutron Sensors for Soil Moisture Monitoring

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Software: Neutron transport was modeled with the adapted Monte-Carlo code „URANOS“, developed by the Physics Institute, Uni Heidelberg. Several tests demonstrated consistency with MCNP.

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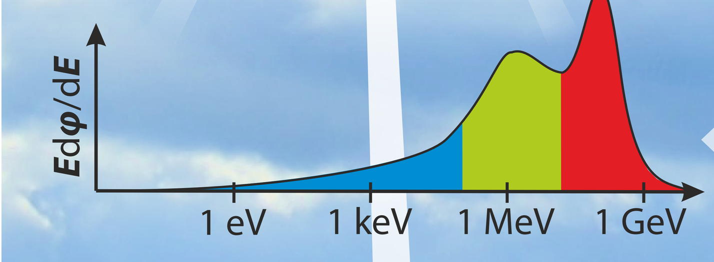
Background: The presence of hydrogen near/in the ground reduces the neutron abundance in a predictable way. Thus, area-average soil moisture can be monitored by detecting cosmic-ray neutrons in air. **Motivation:** The spatial extent of the method was previously estimated to have a 300m radius by using a simplified numerical model that released neutrons in the soil. Recent experiments, however, indicated that the sensor is extraordinarily sensitive to the near field. **Novelty:** We release simulated cosmic-ray neutrons in the atmosphere from a validated energy spectrum. A newly developed software allows to answer open questions on the horizonal weighting, penetration depth and terrain effects. **Consequences:** The footprint is smaller and not constant, which will impact data interpretation and applications.

Cosmic-Ray Neutrons

At the top of the atmosphere, primary cosmic rays generate **high-energy** neutrons, which propagate down and get moderated by air.

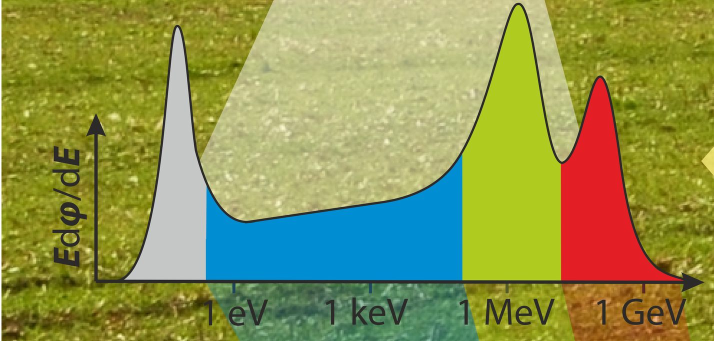


Sensitivity to Water

High-energy neutrons are comparatively insensitive to water. At lower energies, particularly in the **blue** domain, hydrogen can effectively moderate neutrons. Thermal neutrons are slow and sensitive also to other chemical compontents.

New Model

The **full** validated spectrum (from Sato & Niita, RR, 2006) is released above ground.



Old Model

Applies a **low-energy** source in the soil, based only on incoming **high-energy** neutrons.

Mixing in Air

Neutrons are able to travel hundreds of meters from origin (first contact with the soil) to detection.

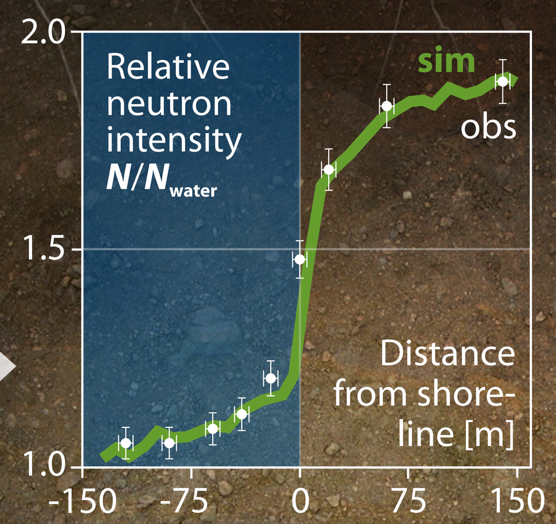
Detection

A moderated ^{3}He detector counts neutrons of the **low-energy** domain.

mod. Detector
bare Detector

Evidence

The revised model was tested by the reproduction of transect experiments across a **water-land** interface. The data also indicates the extent of the footprint and high sensitivity in the near-field.



Radial Sensitivity

The average soil moisture estimate from neutrons is neither an equally nor an exponentially weighted mean. Most of the detected neutrons N probed the soil within the very first meters around a sensor. The **horizontal weighting** rather is:

$$\mathrm{d}N(r,\theta,h)/\mathrm{d}r \approx \begin{cases} F_1\, e^{-F_2 r} + F_3\, e^{-F_4 r}, & r \le 50\,\mathrm{m} \\ F_5\, e^{-F_6 r} + F_7\, e^{-F_8 r}, & r > 50\,\mathrm{m} \end{cases}$$

where $F_i(\theta, h)$

dry soil, $\theta = 1\%$
wet soil, $\theta = 50\%$
humid air $h = 40$ g/m^3
dry air $h = 1$ g/m^3
humid air
dry air

Radial Sensitivity dN/dr (relative units, log-scale)
1
0.1
0.01
0.001

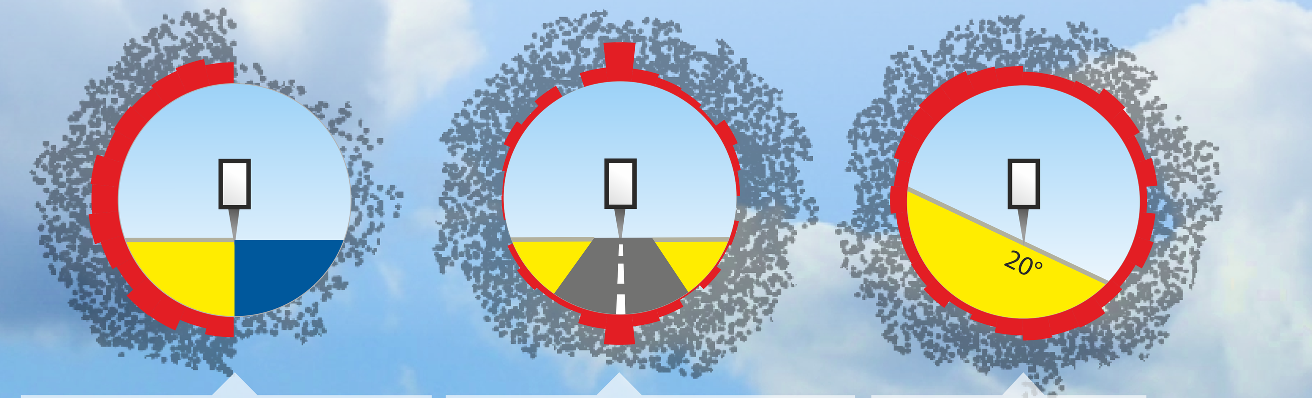
Footprint Radius (θ, h)

The area under the curve represents the total detected neutron intensity. The footprint R_{86} is the distance within which 86% of the detected neutrons originated.

$R_{86}(\theta, h)$: 113 m, 148 m, 171 m, 232 m

0 m, 50 m, 100 m, 150 m, 200 m, 250 m

Anisotropy & Terrain Effect

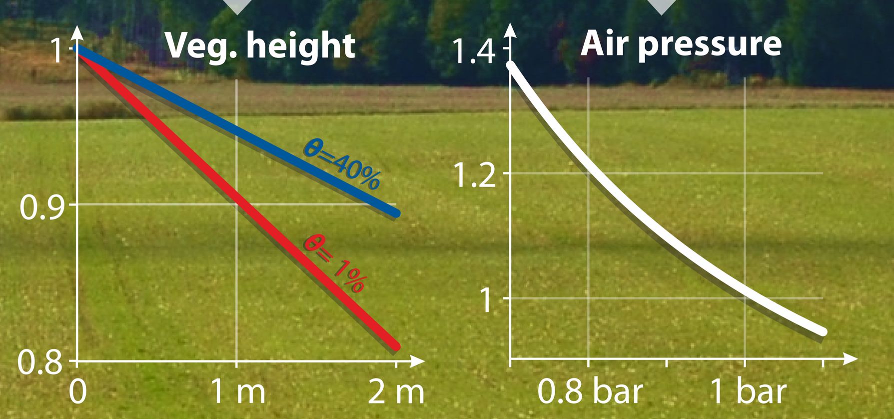


1.7x **larger footprint** over land 3.5x **higher intensity** from land	Nearly **isotropic footprint** 1.2x **higher intensity** from road	**Isotropic footprint** **Isotropic intensity**	θ=5 % h=5 g/m^3

From which direction and distance do neutrons preferably originate (grey)? What is their directional intensity (red)?

Scaling (veg, p)

The footprint size further varies **by a factor** due to vegetation or altitude.



Penetration Depth (r, θ)

Depth D_{86} within which 86% of detected neutrons had contact with the soil.

$$D_{86}(r,\theta) \quad \rho_{bd}^{-1}\left(8.32 + 0.14\,\left(0.97 + e^{-r/100}\right)\frac{26.42+\theta}{0.057+\theta}\right)$$

10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm

θ=50%, θ=20%, θ=10%, θ= 5%, θ= 3%, θ= 1%