Soil Moisture measurement at the hectometer scale
using
CRNS
for
mobile applications

DPG Frühjahrstagung Erlangen

UP 8.2
The Measurement Gap

~ 1 km

via satellite remote sensing (optical, microwave)

< 10 m

via local techniques (electrical resistivity, capacitance, etc) (even neutrons...)

[1] ESA SMOS [http://www.esa.int/Our_Activities/Observing_the_Earth/SMOS/Horn_of_Africa_drought_seen_from_space]
The Measurement Gap

Scales of soil moisture measurements

TDR, TDT, FDR, ...
active neutron probe
NMR
SoilNet
EMI
ERT
DTS
GPR
GNSS-R
SAR, Radiometer, Scatterometers
Gravimetry
RELEVANT SCALES
GRACE
Cosmic Ray Neutron Sensing
.CRNS.
Neutron Response to Water

Rock

Water
active
small distinct domain
thermalization

passive
large area, diffusive
reflection
Neutron Response to Water

passive
large area, diffusive reflection
The Cosmic Neutron Spectrum

\[ \Sigma: 100 \text{ pro (m}^2 \text{ s)} \]

Neutron Flux

Neutron Energy (MeV)
The Cosmic Neutron Spectrum

soil

Neutron Flux

Neutron Energy (MeV)

Base Spectrum
The Cosmic Neutron Spectrum

[Diagram showing neutron flux and energy distribution]

soil

Evaporation

Neutron Energy (MeV)

Neutron Flux
The Cosmic Neutron Spectrum

Elastic Scattering

Neutron Flux

Neutron Energy (MeV)

soil

Helmholtz Centre for Environmental Research - UFZ
The Cosmic Neutron Spectrum

soil

Neutron Flux

Neutron Energy (MeV)

Neutron Flux

Thermalized

1.5 x 10^{-3}

1.0 x 10^{-3}

0.5 x 10^{-3}

0
The Cosmic Neutron Spectrum

- Air: 60% humidity at 20°C
- Soil: 37.5% SiO₂ + 12.5% Al₂O₃
- Water content per vol:
  - 0.00
  - 0.05
  - 0.10
  - 0.15
  - 0.20
  - 0.30
  - 0.50
  - 0.99

Neutron flux [a.u.]

Neutron Energy (MeV)

Energy [MeV]

10⁹, 10⁸, 10⁷, 10⁶, 10⁵, 10⁴, 10³, 10², 10¹, 10⁰, 10⁻¹, 10⁻², 10⁻³, 10⁻⁴

1.5 x 10⁻³
The Cosmic Neutron Spectrum

Relative neutron intensity $N/N_0$

- simulations (this work)
- fitted eq. C1 (this work)
- Desilets et al. 2010

Neutron Energy (MeV)
The Footprint

How far do reflected neutrons travel?
How far do reflected neutrons travel?

Köhli et Schrönn et al.
*Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons*
Water Resources Research, 51, 5772-5790
Penetration Depth

Penetration Depth $D_{86}$ [cm]

Radial Distance $r$ from the Sensor [m]

Depth
The Equipment
The CRNS Sensor

- GSM antenna
- neutron pulse module (NPM)
- datalogger and cell modem
- bare $^3$He tube (thermal detector)
- moderated $^3$He tube (epithermal detector)
- charge controller
- maintenance-free battery (12V)
- connection to external sensors ($T$, $h$), rain gauge, solar panel
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M. Zreda et al. (CRNS Website)
URANOS
Ultra Rapid Adaptable Neutron-Only Simulation for Environmental Research

Physikalisches Institut
Heidelberg University

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
Layers are arranged in the vertical directions, representing different materials or 2D gridded patterns. Position y denotes the depth below surface (s=0) in [m] and refers to the upper edge of the layer. Layers override topological presets.

<table>
<thead>
<tr>
<th>Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<tr>
<td>3</td>
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<td>10</td>
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<tr>
<td>11</td>
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<tr>
<td>12</td>
</tr>
</tbody>
</table>

**Topological presets (water, land):**
- None
- River, width [m]: 10
- Coast or x [m]: 6
- Island, diameter [m]: 10
- Lake, diameter [m]: 10

**Estimated Radial Neutron Distribution at Sea Level:**

- **Auto Refresh**
- **Log**

**Integral Range:** 220 m
- **Coverage:** 87.34%
Inhomogeneous Terrain

topography
Inhomogeneous Terrain

topography

model

200 m
Inhomogeneous Terrain

topography

model

simulation
Mobile CRNS
Local Effects
Local Effects

Intensity $dN/dr$ of detected neutrons [arb. units]

- Red: $\theta = 3\%$
- Blue: $\theta = 50\%$

$W_r(\theta, h)$ analyt. fit

Footprint radii $R_{63}, R_{86}$

Radial distance $r$ [m]

Near field peak

63% at 50 m

86% at 200 m

Long tail
Local Effects

Normalized horizontal weight

- **Conventional**, $W_{\text{conv}}$
- **Revised**, $W_r(h, \theta)$

<table>
<thead>
<tr>
<th>Condition</th>
<th>Humidity</th>
<th>Soil moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>$h = 5 \text{ g m}^{-3}$</td>
<td>$\theta_v = 10%$</td>
</tr>
<tr>
<td>Humid</td>
<td>$h = 10 \text{ g m}^{-3}$</td>
<td>$\theta_v = 20%$</td>
</tr>
<tr>
<td>Wet</td>
<td>$h = 15 \text{ g m}^{-3}$</td>
<td>$\theta_v = 40%$</td>
</tr>
</tbody>
</table>

$W_r^*$ average approximation (eq. B1)
Local Effects

Pool Transect
Local Effects

Pool Transect
Local Swimming Pool Effects

Intensity vs. x [m]

- Swimming Pool Transect
- Pool 20 cm depth
- Moderated tube
- Data 50 cm
- Data 165 cm
- Cyl 0.5m TeV-100keV
- Sim 50 cm
- Sim 200 cm
Road Simulations
Road Simulations

(a) Stone road, $\theta_{\text{road}} = 3\%$

- width $w = 3\, \text{m}$
- width $w = 5\, \text{m}$
- width $w = 7\, \text{m}$

(b) Asphalt road, $\theta_{\text{road}} = 12\%$

- width $w = 3\, \text{m}$
- width $w = 5\, \text{m}$
- width $w = 7\, \text{m}$
Ex B: Parallel tracks at Sheepdrove Farm

gravel/stone road

rover tracks

asphalt/stone road
Road Experiments

a Ex B: Parallel tracks at Sheepdrove Farm

b Ex B: Observed vol. soil moisture in %
- O gravel/stone road
- ● asphalt/stone road
- variability along each track (400 m)

uncorrected

Distance from road center, r in m
Road Experiments

**Ex B: Parallel tracks** at Sheepdrove Farm

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**Ex B: Observed vol. soil moisture** in %

- O gravel/stone road
- • asphalt/stone road
- variability along each track (400 m)

**Graph:**
- **uncorrected**
- **corrected**

**Distance from road center, r in m**
Ex A6 2014 May 08  Road

PDF in overlap area

- Rover: 14.6 ± 4.2
- TDR: 22.2 ± 6.3
**Mobile CRNS**

### Ex A6 2014 May 08 Road

**PDF in overlap area**
- **Rover**: 14.6 ± 4.2
- **TDR**: 22.2 ± 6.3

### Ex A6 2014 May 08 Road corrected

**PDF in overlap area**
- **Rover (F_2)**: 20.4 ± 4.2
- **Rover (F_2)**: 21.0 ± 5.5
- **TDR**: 22.2 ± 6.3
The Measurement Gap

Scales of soil moisture measurements

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[Diagram showing different scales of soil moisture measurements and relevant techniques]
The Measurement Gap

Scales of soil moisture measurements

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- GNSS-R
- SAR, Radiometer, Scatterometers
- Mobile CRNS

And now here
Cosmic-Ray Neutron Sensing

Outlook:
Cosmic-Ray Neutron Sensing

- provides an average soil moisture measurement over several hectares and 0.5 m in depth
- can be understood by Monte-Carlo transport modelling
- road effect, small scale variations, inhomogeneous soil moisture patterns can now be corrected

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Outlook

- development of larger detectors for mobile sensing
- application in heterogeneous environments
- snowpack monitoring