Virtual DPG meeting 2021 -- UP 4.3

Moisture and humidity dependence of the above-ground CR neutron intensity revised

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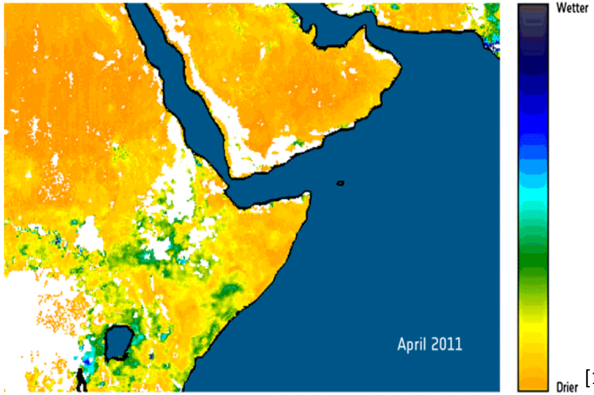
Cosmic Sense

DFG FOR 2394

> The scale gap for soil moisture measurements

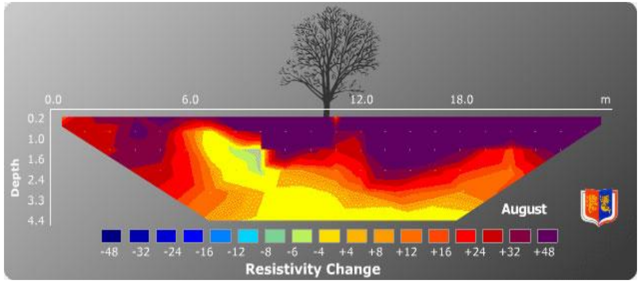
~ 1 km



[1]

via
satellite remote sensing
(optical, microwave)

< 10 m

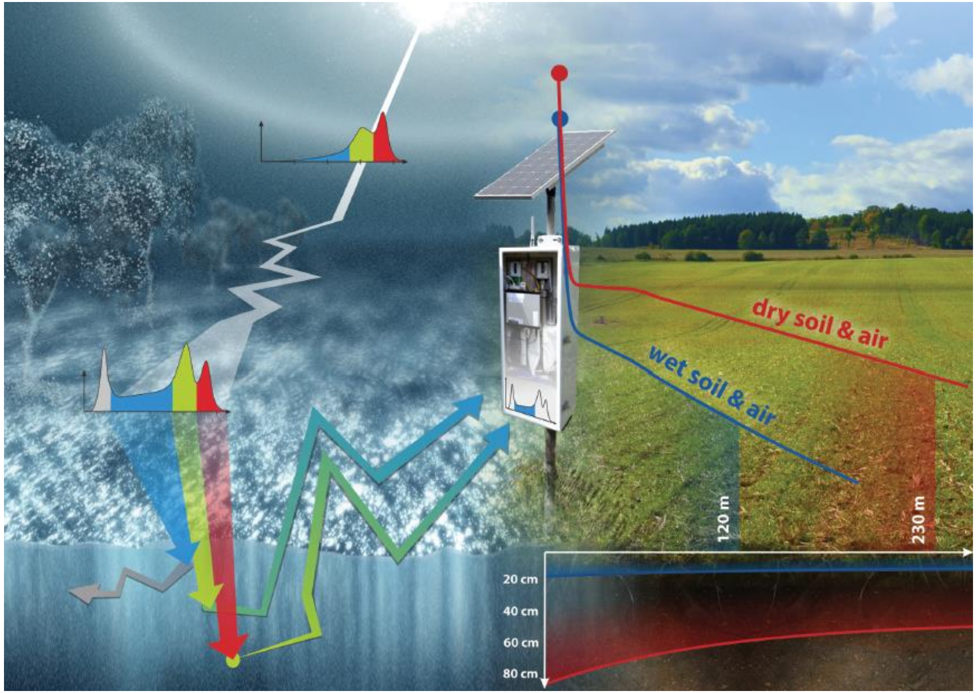


[2]

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

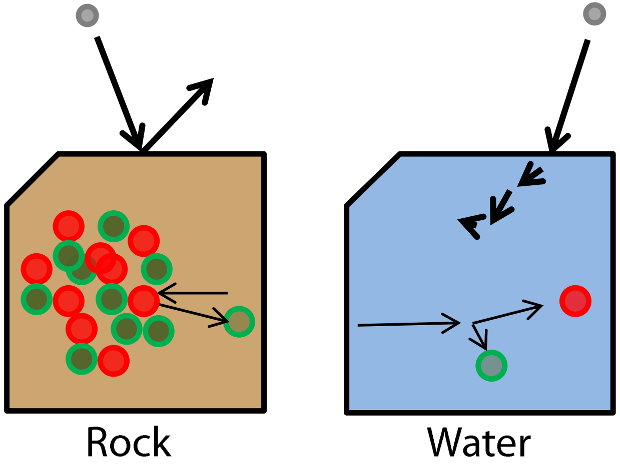
[1] ESA SMOS (http://www.esa.int/Our_Activities/Observing_the_Earth/SMOS/Horn_of_Africa_drought_seen_from_space)
[2] The Clay Research Group (http://www.theclayresearchgroup.org/images/ert.jpg)

Cosmic-Ray Neutron Sensing



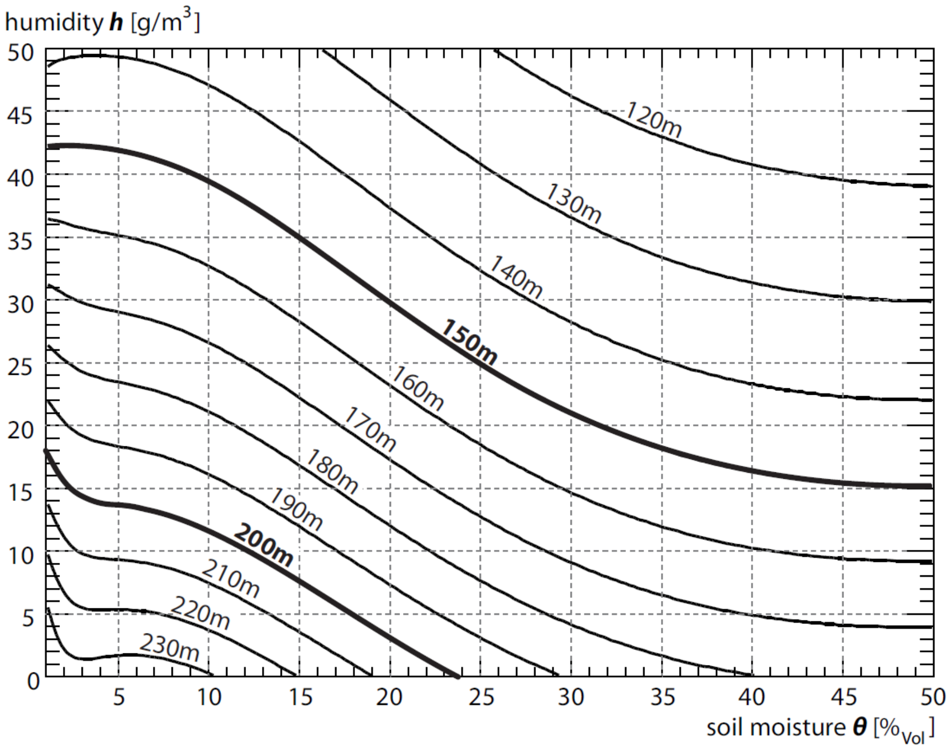
Close the scale gap by CRNS

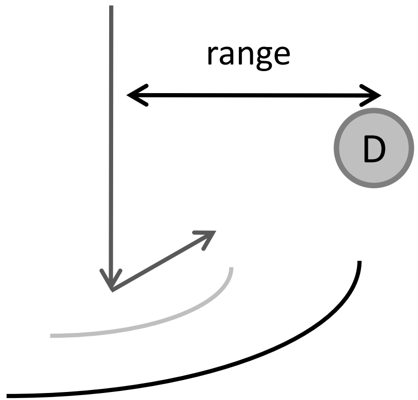
In water neutrons disappear, everything else reflects



The Footprint

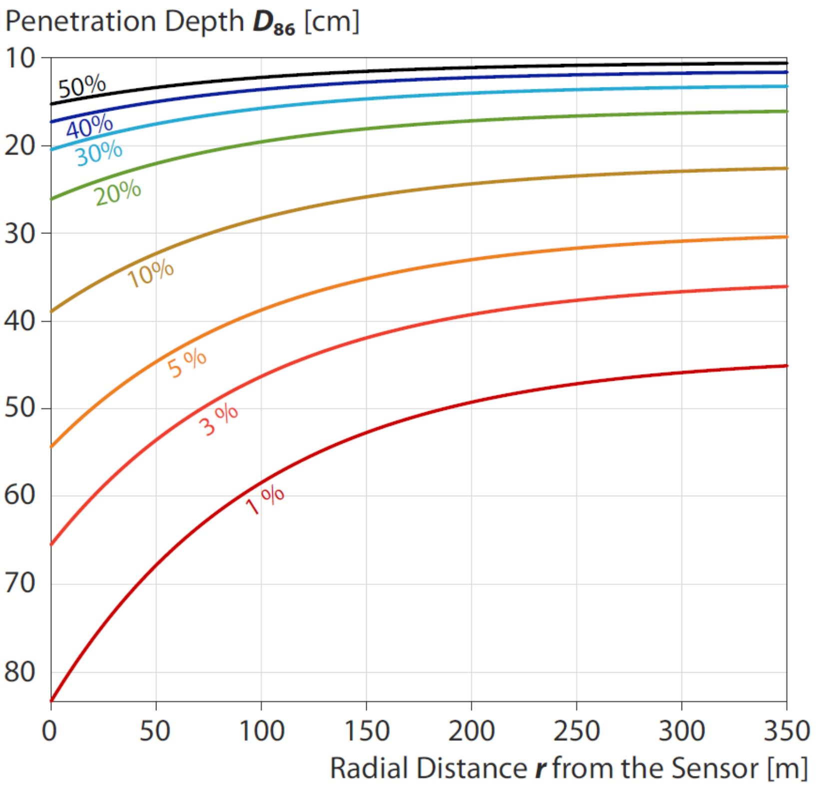
How far do reflected neutrons travel?

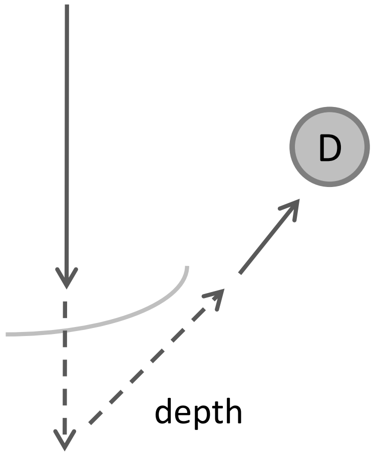




M. Köhli et al.
Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons
Water Resources Research, **51**, 5772-5790 DOI: 10.1002/2015WR017169

> Penetration Depth





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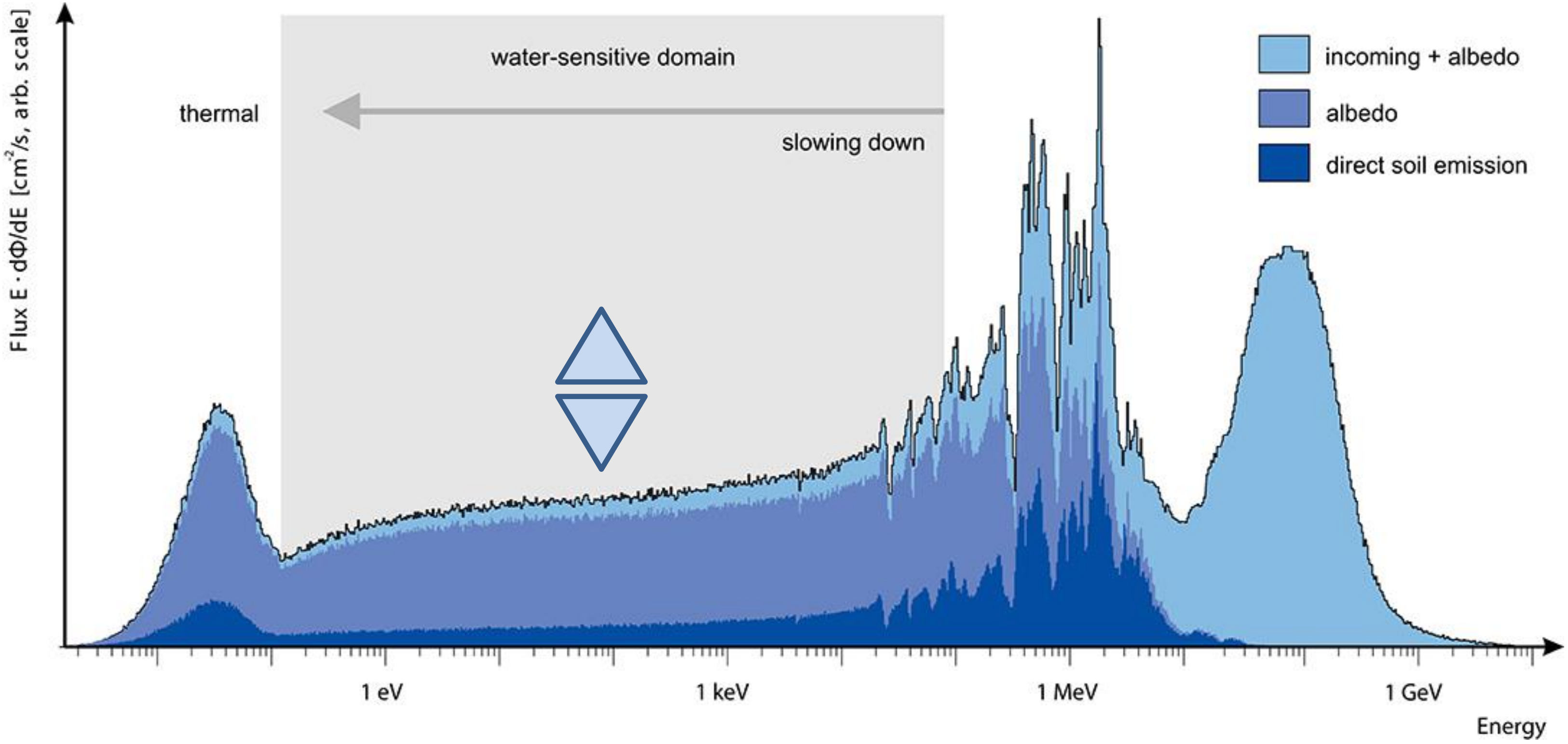
> The Cosmic-Ray Neutron Spectrum



M. Köhli et al.
Soil Moisture and air humidity relation dependency of the cosmic-ray neutron intensity
Front. Water, **2**, DOI: 10.3389/frwa.2020.544847

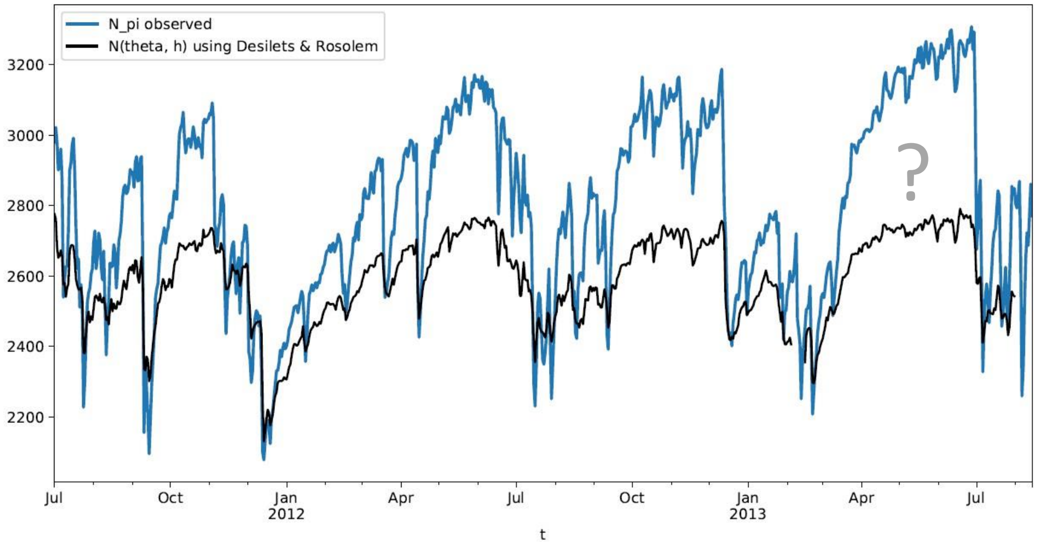
Soil Moisture Measurement by Cosmic-Ray Neutrons

Intensity to the environmental water content relation

Current (Desilets*) Method:

$$\theta(N) = \frac{a_0}{\frac{N}{N_0} - a_1} - a_2 \qquad (1)$$

Hyperbola with 3 fixed and one detector-specific parameter



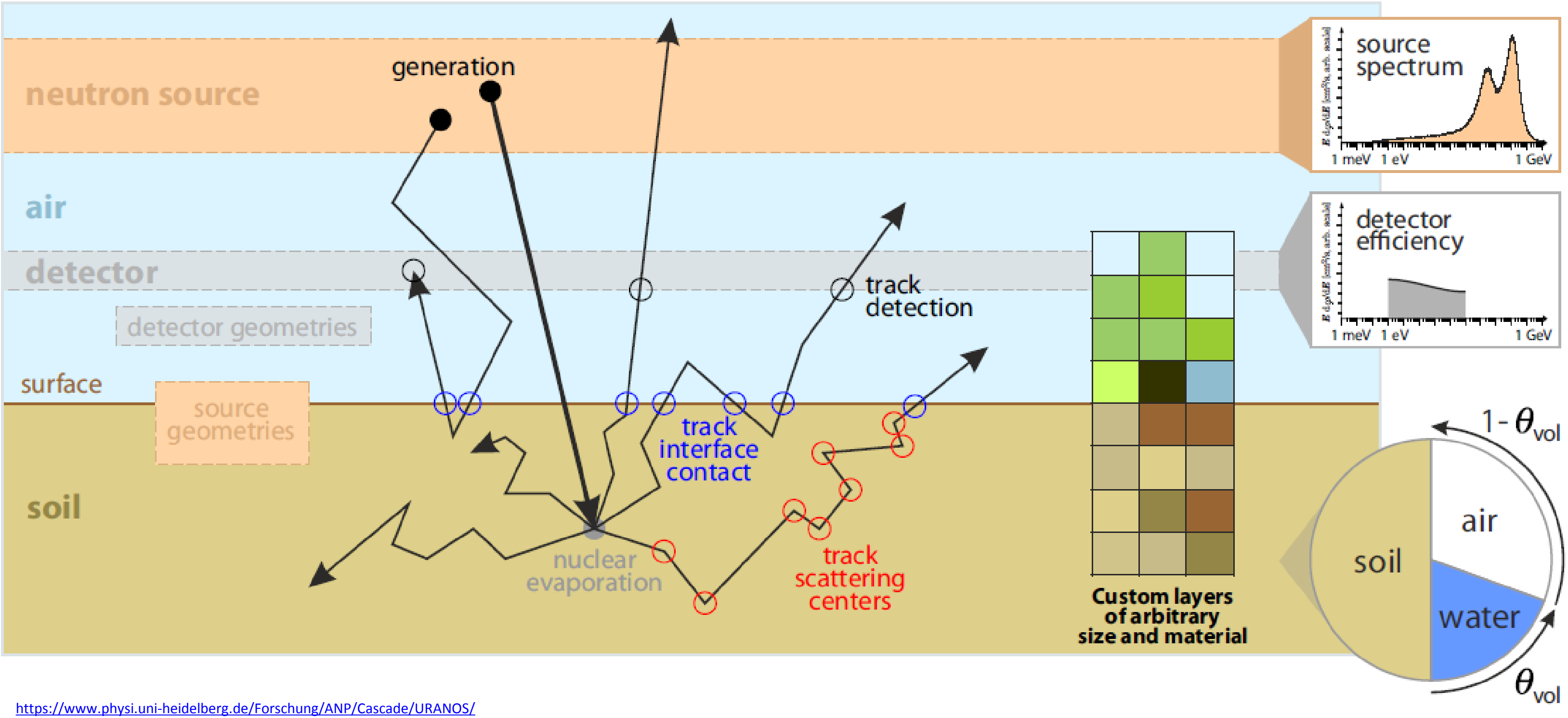
Time series from Santa Rita, US, provided by T. Franz

However, especially in dry regions this hyperbola underestimates the signal strength.
Many attempts to re-parametrize the Hyperbola lead to a series of site-specific calibration sets.

*D. DESILETS, M. ZREDA, and T.P.A. FERRÉ. “Nature’s neutron probe: Land surface hydrology at an elusive scale with cosmic rays.” In: *Water Resources Research 46(11) (2010), W11505.*

> Methods

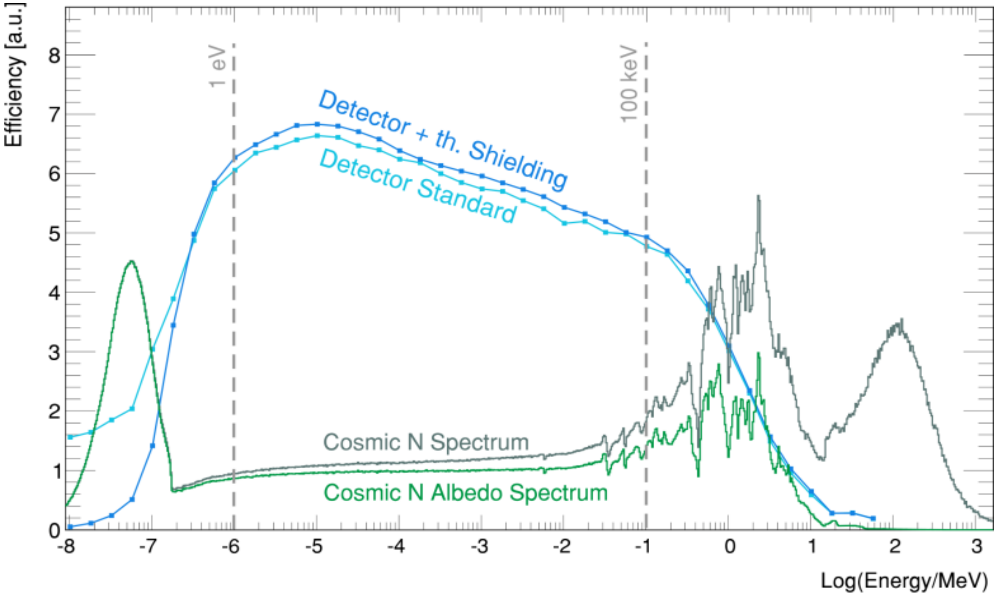
The simulation toolkits used in this study are MCNP 6.2 and URANOS. The air medium consists of 78% nitrogen, 21% oxygen and 1% argon usually at a pressure of 1020 mbar. The soil consists of 50%Vol solids and a scalable amount of H2O. The solid domain is comprised of 75%Vol SiO_2 and 25%Vol Al_2O_3 at a compound density of 2.86 g/cm^3. The input spectrum used in this work relies on the cosmic-ray propagation models by Sato et al.

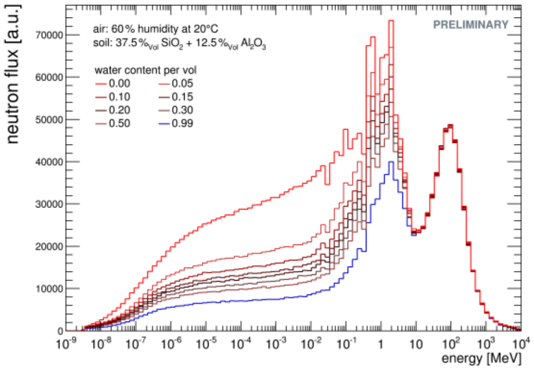


https://www.physi.uni-heidelberg.de/Forschung/ANP/Cascade/URANOS/

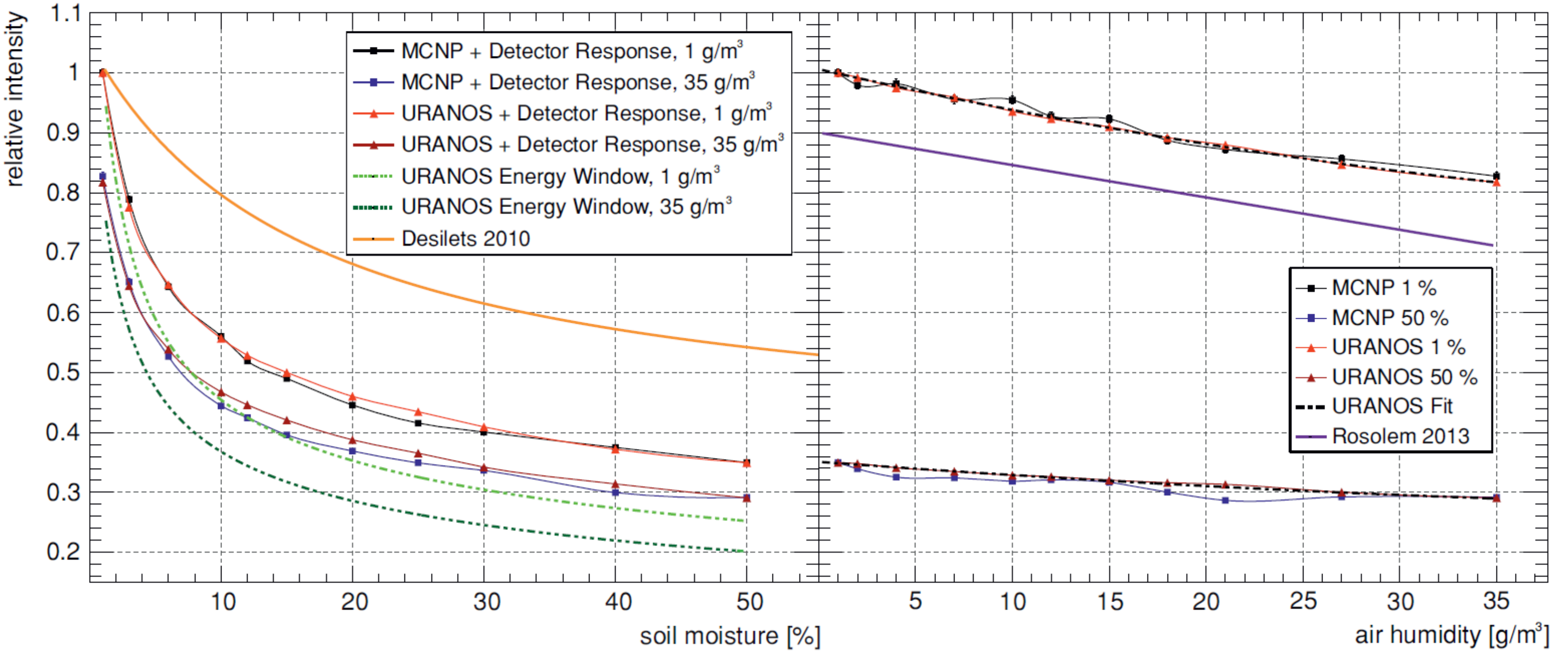
> Detector Response Function

Simulations for the neutron response of commonly used CRNS detectors show that the energy window of highest response ranges from 0.1 eV to 10^6 eV and peaks between 1 eV and 10 eV. A signicant fraction of neutrons are contributing to the sensor signal below and above the hitherto accepted range of (10^2 to 10^4) eV. Contributions by thermal neutrons contribute up to 20 % to the sensor signal. Yet, the footprint of thermal neutrons is much smaller and they are subject to near-field effect. A thermal neutron shield can suppress this contribution.





Simulation Results



The simulation results show that using fixed upper and lower boundaries for scoring the neutron flux (energy window) the intensity scaling as a function of soil moisture is significantly higher. While the latter reduces the intensity by approximately 75 %, using a detector response function reduces the measured flux by 65 %.

For humid compared to dry air the maximum achievable count rate is reduced by 20 %. This quantitatively agrees with Rosolem et al. (2013) who studied the change from dry to 22 g/m^3. However, a strictly linear relationship for water vapor cannot be verified. The presented reduction rate of 0.0054 per gram air humidity seems to hold only for dry conditions.

R. ROSOLEM et al. “The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System.” In: *Journal of Hydrometeorology* 14(5) (2013), pp. 1659–1671.

Revision of the Intensity Relation

We call the intensity equation derived from our simulations **UTS** (**U**niversal **T**ransport **S**olution)

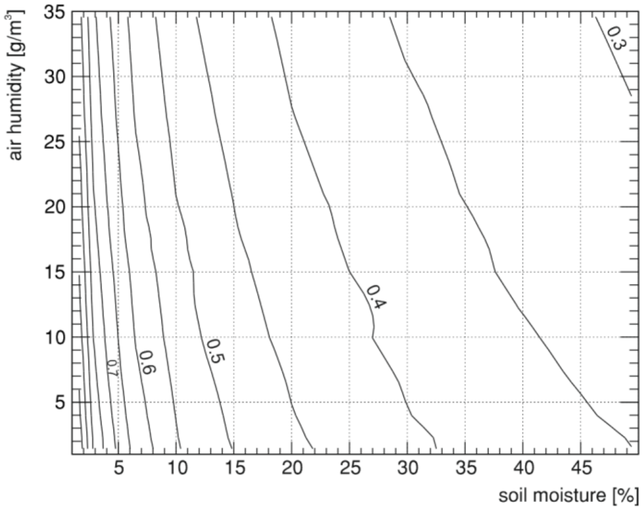
In order to apply it to soil moisture retrieval it has to be inverted numerically

$$I(\theta, h) = \frac{p_1 + p_2\theta}{p_1 + \theta}\left(p_0 + p_6 h + p_7 h^2\right) + \exp\left(-p_3\theta\right)\left(p_4 + p_5 h\right)$$

2-parameter hyperbola

exponential addition

humidity correction

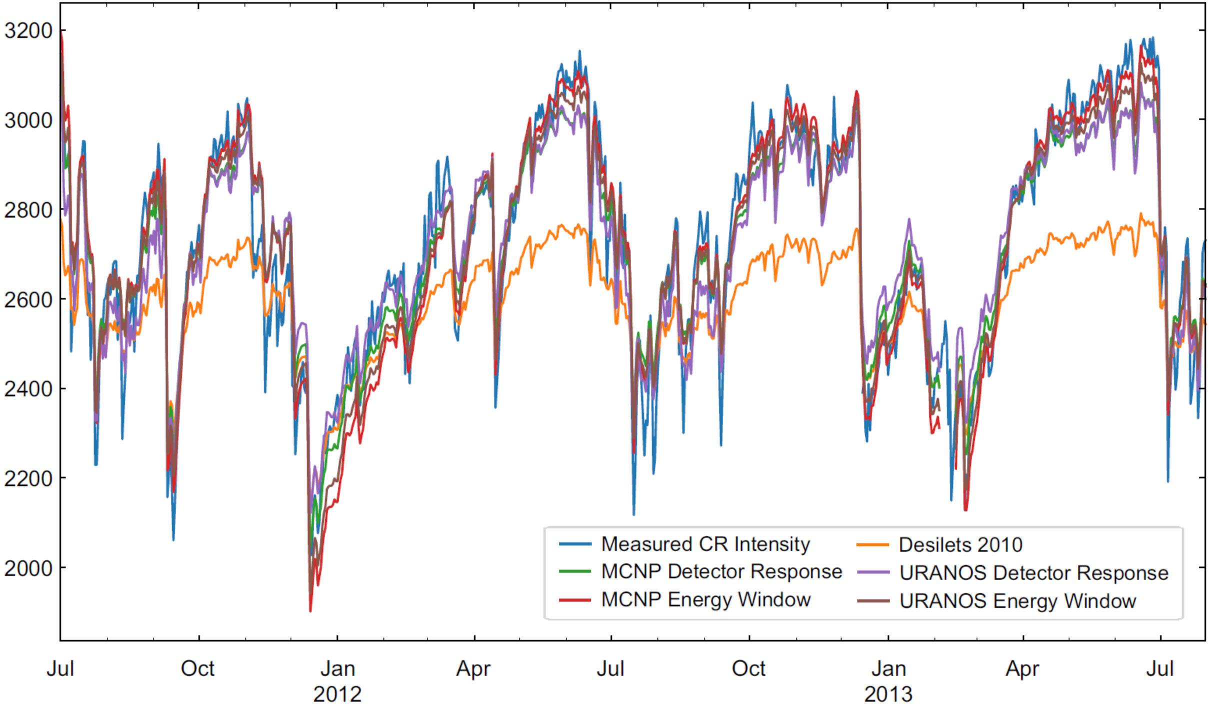


The major outcome of this study is that the Desilets equation is far not steep enough to describe especially measurements in dry regions. The hyperbolic characteristics reflects well local gradients, which is the reason why different parameterisations of this equation led to site-specific solutions. However, in different studies typical calibration plots indicate a more steep relation. Especially when tuned to rather moist conditions the gradient from the Desilets equation is able to follow the simulations over a broad range of the variable space. The reason is that the solution for the above-ground neutron flux, can require an additional exponential term , which leverages the intensity changes especially for dry conditions.

First, air humidity corrections are non-linear, yet the relative changes can be linearized, and second, the intensity scaling is much steeper than until now assumed based on the Desilets equation.

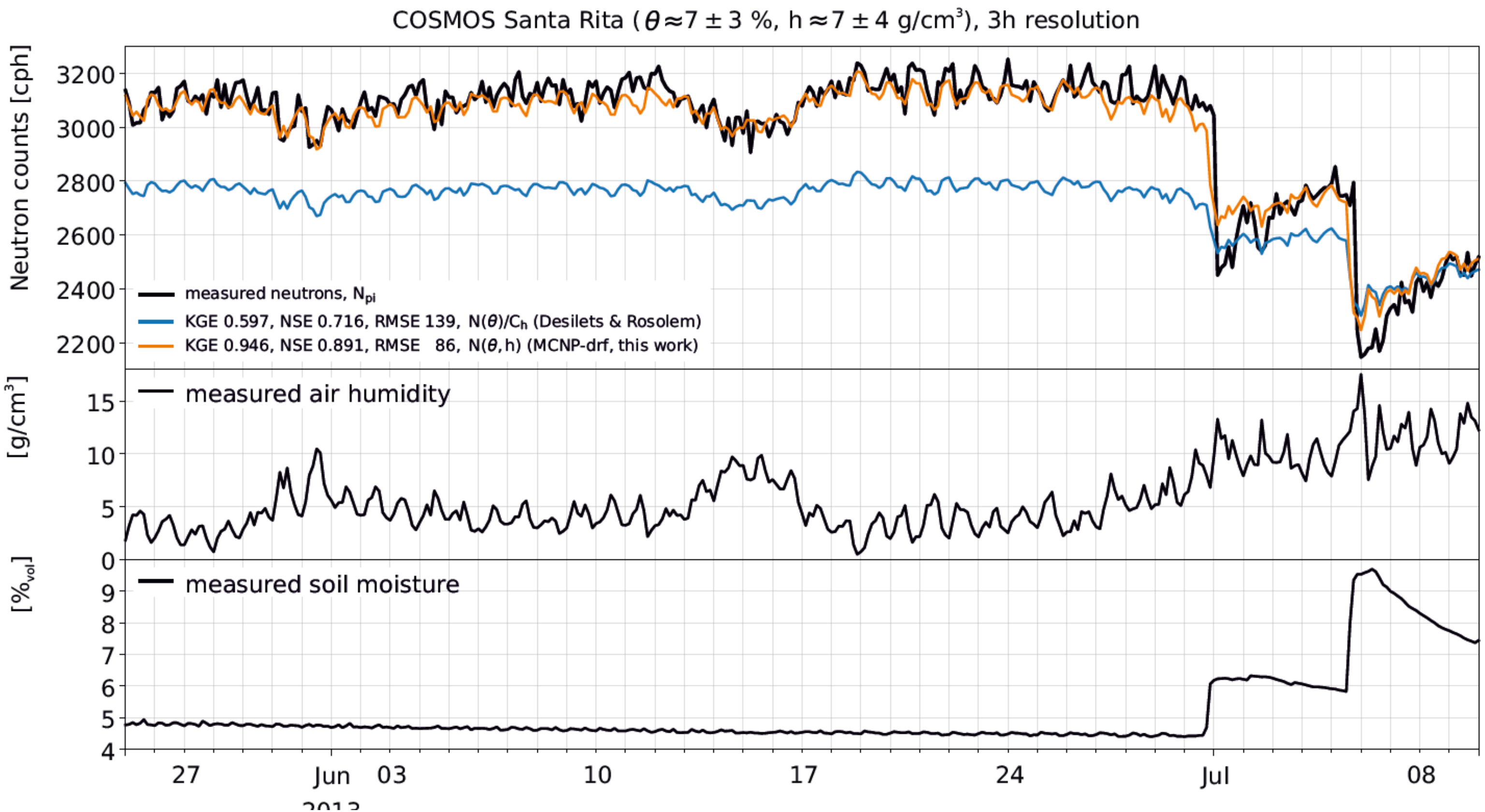
Above-ground neutron intensity as a function of air humidity and soil moisture simulated by URANOS applying a simulated detector response function

Experimental verification – dry conditions

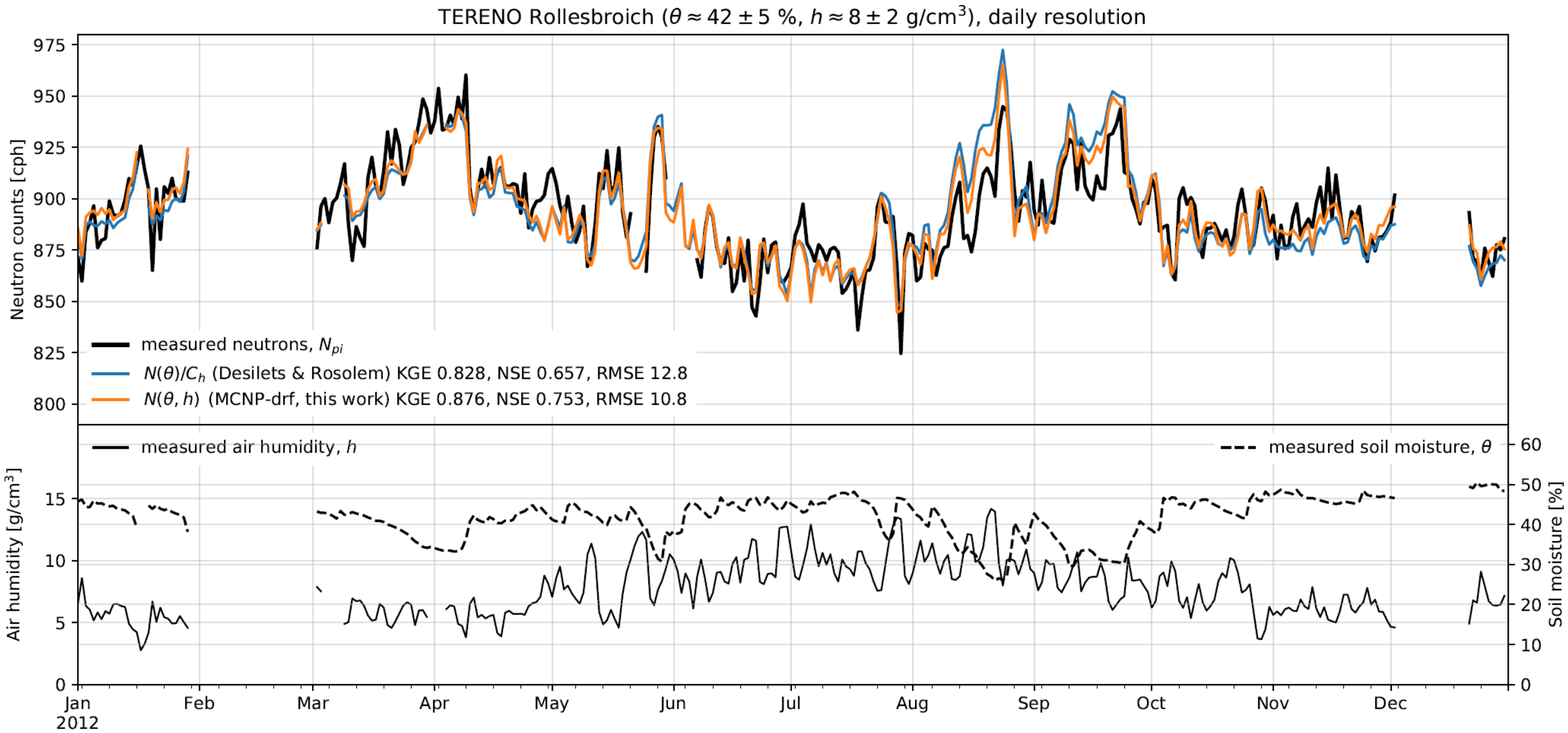


The Santa Rita Experimental Range offers large variations in soil moisture and air humidity. The intensity measured by the neutron counter with a 24-h running average is shown in blue. Soil moisture from the TDT network has been converted to neutron intensity using different approaches. In comparison to the Desilets equation (1) with the water vapor correction (Rosolem et al., 2013) (orange) the UTS-formula presented in this work performs significantly better. The detector response simulations show a lower absolute intensity change than the energy window parameterizations, which in some cases fit slightly better to the data. The sharp spikes originate from air humidity variations, which are also better described by the approach of this work than the hitherto existing one.

Experimental verification – air humidity



> Experimental evidence – wet conditions



Data from Rollesbroich (R. Baatz)

> Résumé

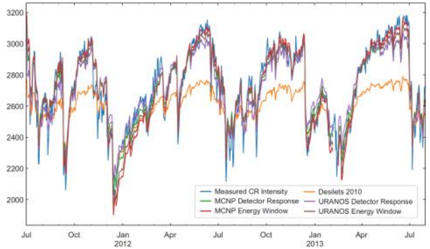
CRNS – soil moisture sensing at the hectometer scale

- A new **CRNS intensity function** found by understanding **the contributions** and **improving the corrections of CR neutrons to the signal.**

  The UTS function for soil moisture and humidity:

$$I(\theta, h) = \frac{p_1 + p_2\theta}{p_1 + \theta}\left(p_0 + p_6 h + p_7 h^2\right) + \exp\left(-p_3\theta\right)\left(p_4 + p_5 h\right)$$

- First data blind validation very successfull



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