Cosmic-ray neutron sensing: from an inconvenient noise to a worldwide method for soil moisture estimation (and not only)

G. Baroni[1], L. Stevanato[2,3], S.Gianessi[1], M.Polo[2,3], M. Lunardon[2,3]

(1) Department of Agricultural and Food Sciences, Alma Mater Studiorum University of Bologna (Italy)
(2) Department of Physics and Astronomy, University of Padova (Italy)
(3) Finapp srl

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FINAPP
"Life from cosmos"

Workshop on Nuclear Technologies for Agriculture 4.0
18 December 2020

Outline

1. Soil moisture: a call for intermediate-scale non-invasive observations
2. An overview on cosmic-ray neutron sensing – CRNS
3. Where do we stand and go with CRNS?
4. Outlook

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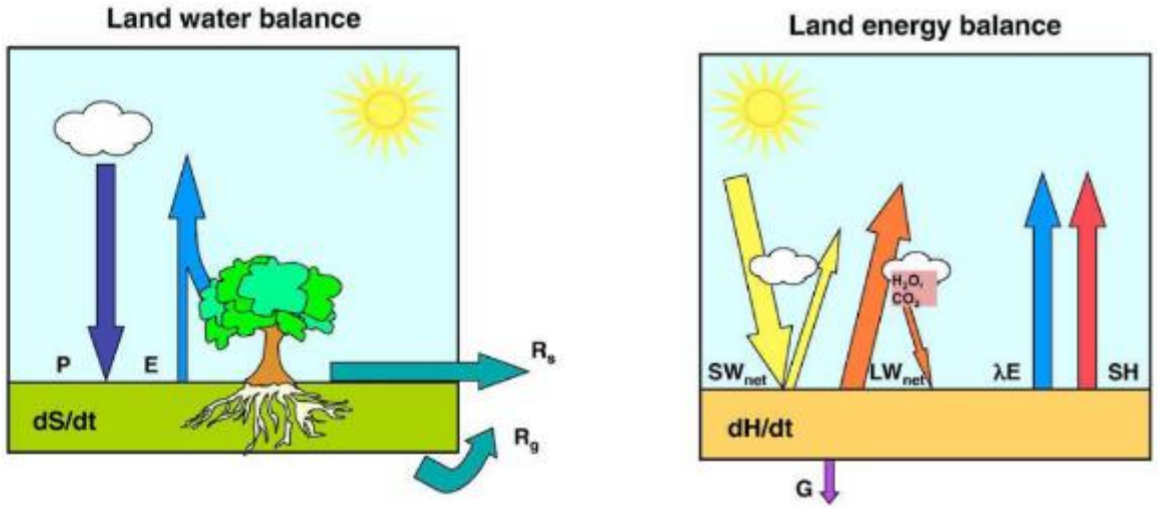
The role of soil moisture

- Soil moisture (dS/dt) plays a crucial role in controlling the partitioning of water and energy fluxes at the land-surface

- For this reason, the study of this variable is of primary importance in many applications e.g., weather prediction, flood and irrigation, agricultural and forest management



from Seneviratne et al. (2010)

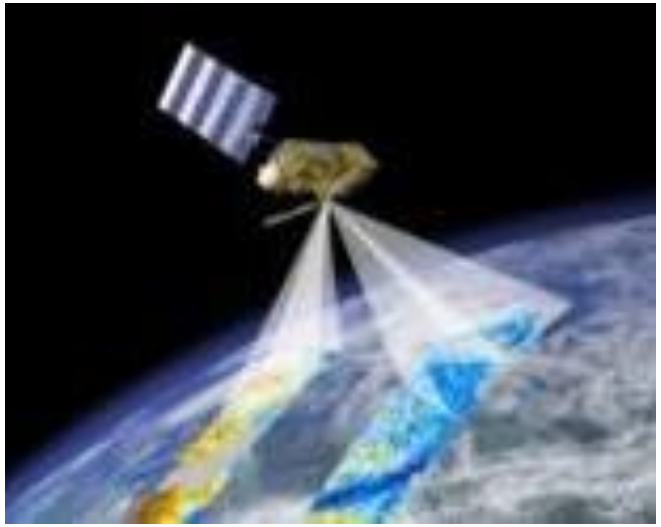
Soil moisture observations

Many methodologies developed **to estimate soil moisture** at different spatial scales

Point-scale

Proximal sensing: intermediate

Remote sensing: large-scale



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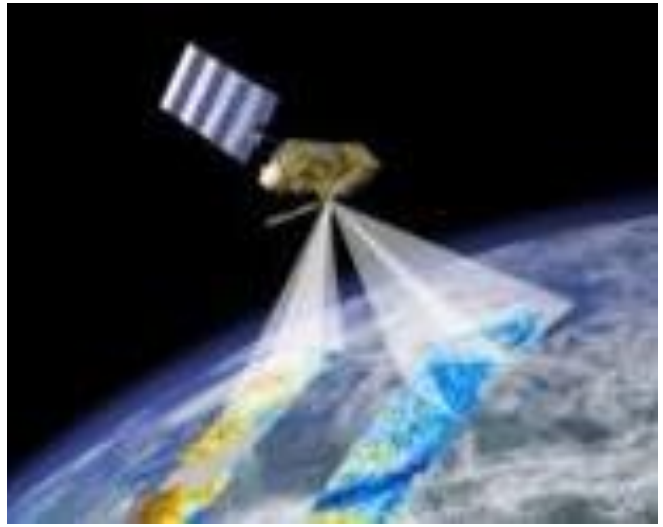


1. None of them is a direct soil moisture measurement
2. They are all based on a “strong” correlation of a signal with soil moisture

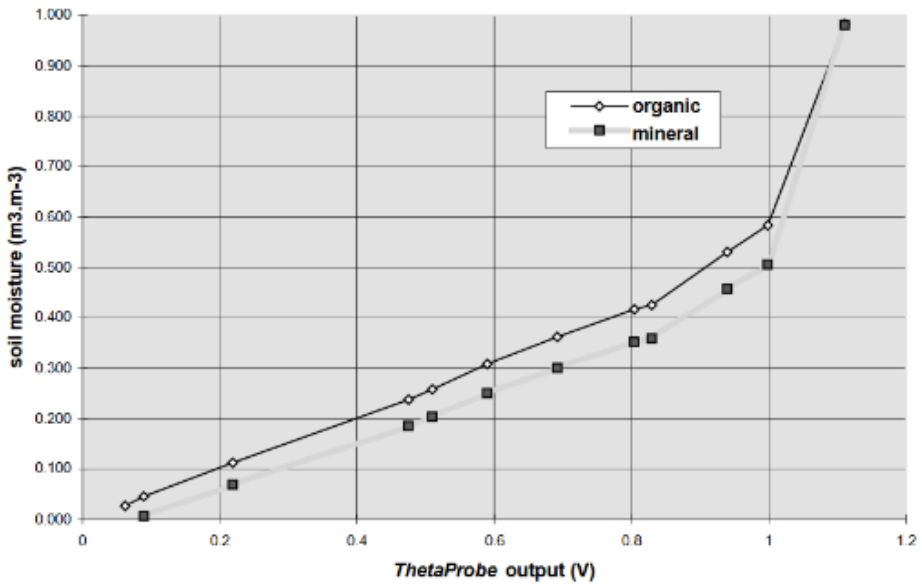
Direct soil moisture measurements vs. estimation

Gravimetric (weighted) method based on soil samples is the only **direct measurement**

- Time consuming, manpower, destructive

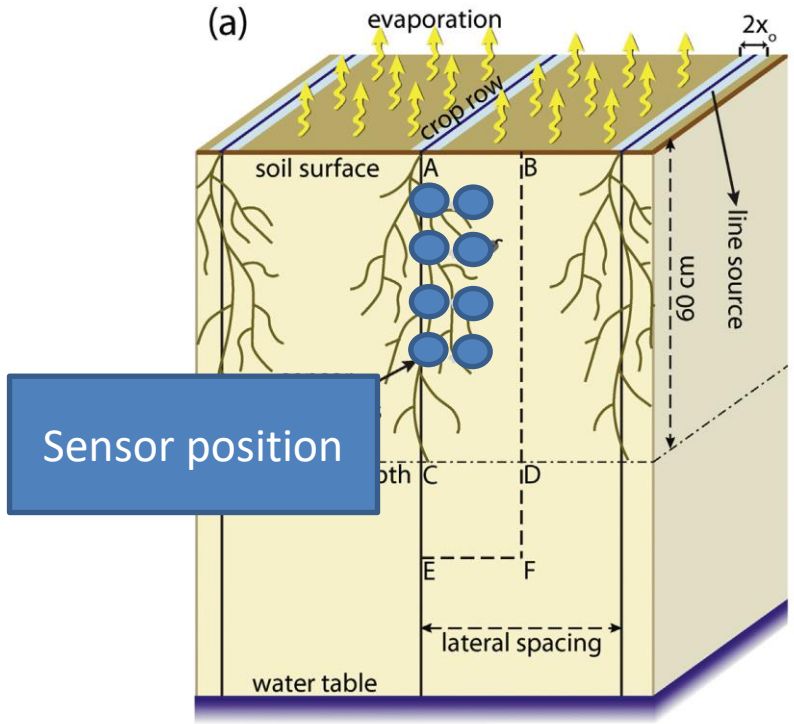
Alternatively, we use **geophysical methods (independent by the scale):** we measure by a sensor another variable strongly correlated with soil moisture

- We need to establish a relation (function) to estimate soil moisture
- We need often to calibrate the function (not unique)



What is the problem with point-scale observations?

- Traditionally, point-scale soil moisture methods used in many applications like agriculture
- They supported many studies and findings, but they suffer from the inherent **spatial variability of the soil-plant systems**



From Soulis et al. (2015)

Soil moisture **sensors positioning** and accuracy considerably affect irrigation efficiency in soil moisture-based drip irrigation scheduling systems

A call for intermediate-scale non-invasive observations

Similar limitations have been highlighted in several applications and provide the basis for further development of intermediate-scale soil moisture observations

During the last decades, **several approaches** emerged:

Ground penetration radar (GPR); GNSS; gravimetry, Electromagnetic induction (EMI); **cosmic-ray neutrons detector (CRNS); gamma-ray spectrometer (GRS)**

Key characteristics

- Different signal / wave lengths
- Passive or active
- Specific temporal and spatial resolutions
- Different precision-accuracy
- Different costs

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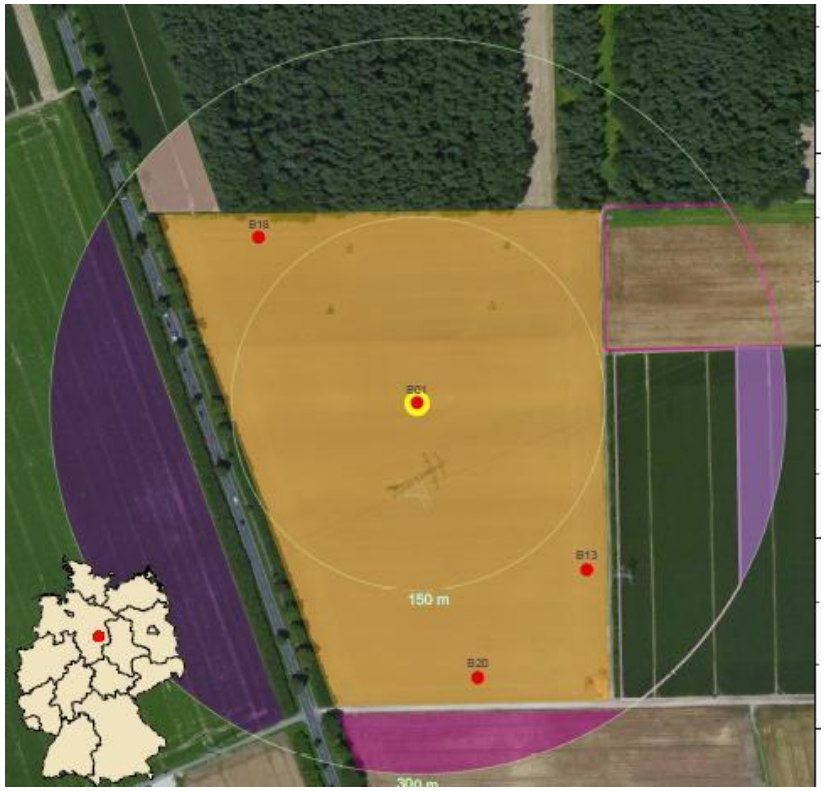
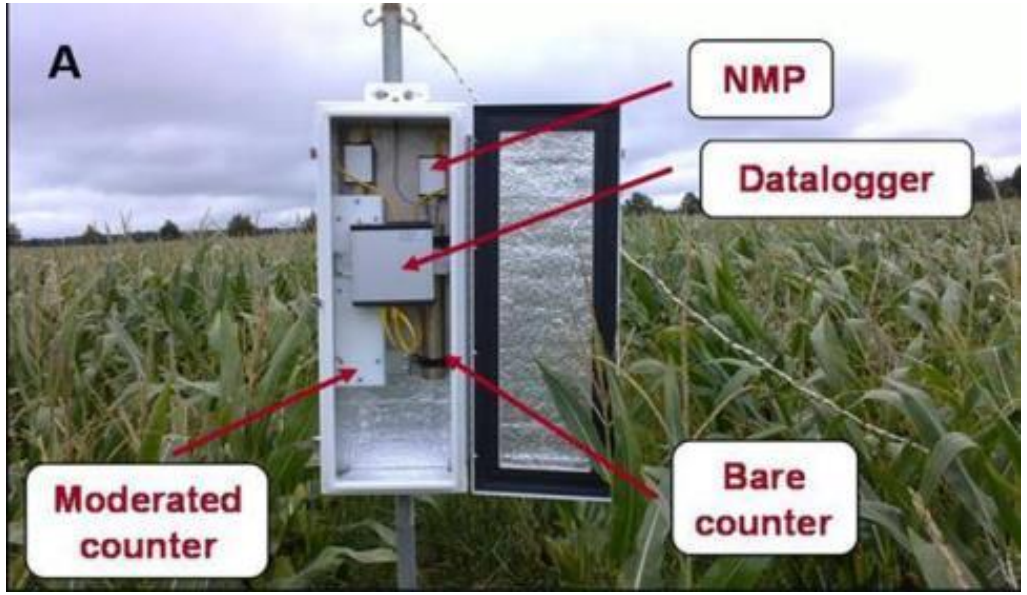
Cosmic-ray neutron sensing - CRNS: what is it?

Introduced to the hydrological community by Zreda et al. (2008) and Desilets et al (2010)





Some key aspects

Non-invasive method

Passive neutron probe

Intermediate scale: ~150 m radius, 40 cm soil depth

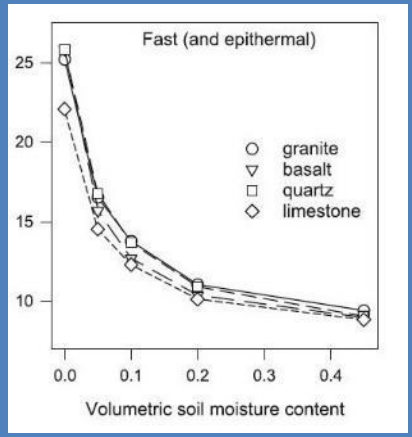
Temporal resolution ~hours

Low maintenance

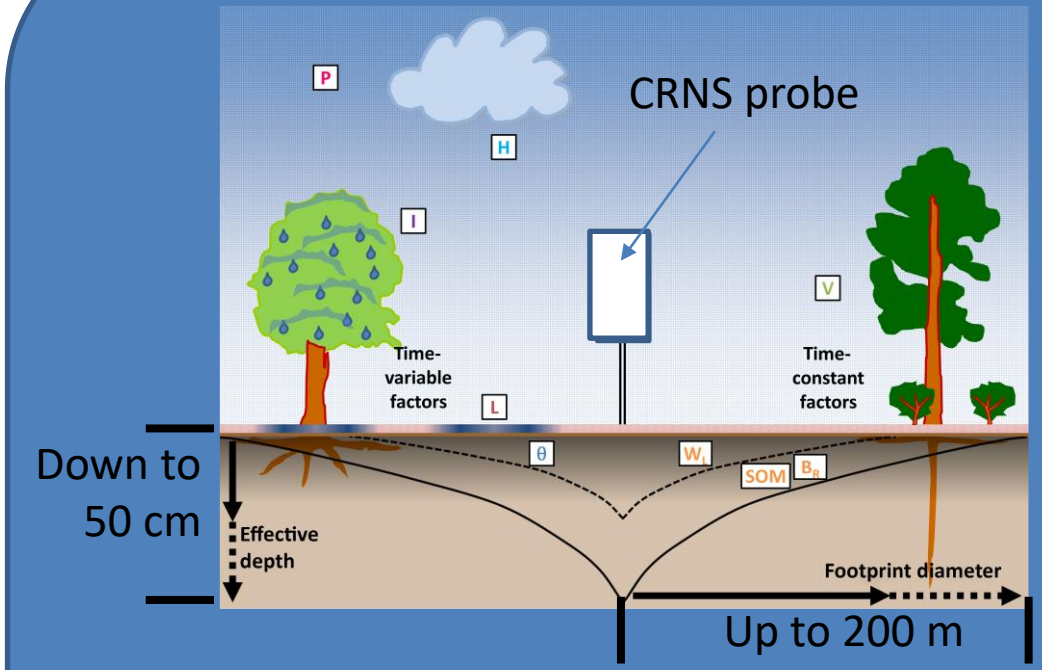
CRNS - how does it work?...in three steps

1. Cosmic-rays generate neutron at the land surface

2. Epithermal neutrons are inversely correlated to hydrogen (soil moisture)



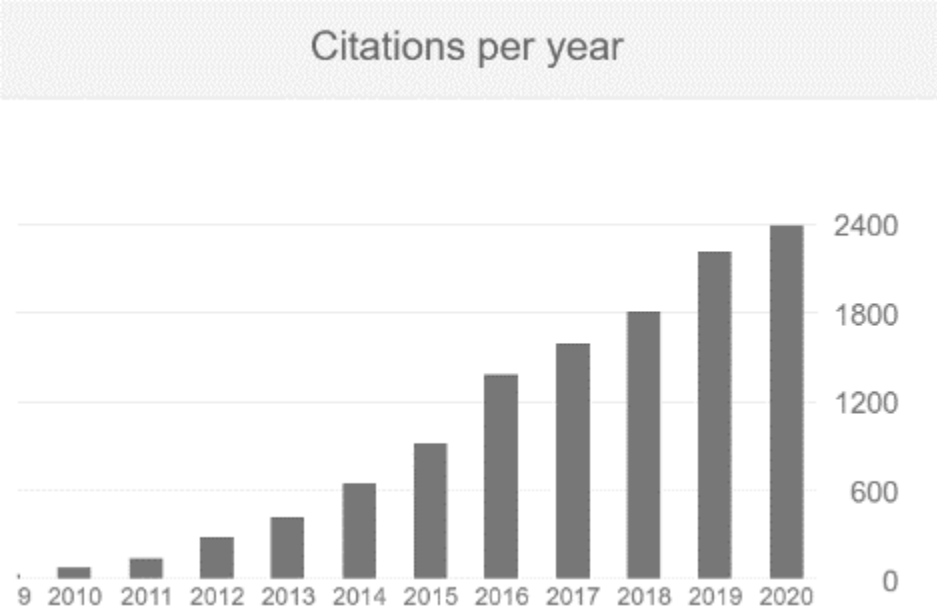
Modified from Heidbüchel et al. (2016)



3. A neutron detector installed above ground estimates soil moisture non invasively at large scale

A big success….

- More than 200 probes installed over the World
- Several national observatories network (US, Australia, UK, Germany, India, South Africa..)
- Biannual meeting of the "CRNS community" (https://cosmos.physi.uni-heidelberg.de/)



https://scholar.google.com/citations?view_op=list_works&hl=en&user=5suST7AAAAAJ

Groups working on CRNS

Why such a success? A brief historical overview

From D.Hillel Environmental Soil Physics

- Neutron probe dated back 1950
- If you asked who used that…
  The best soil moisture sensor ever!
- But based on active neutron source

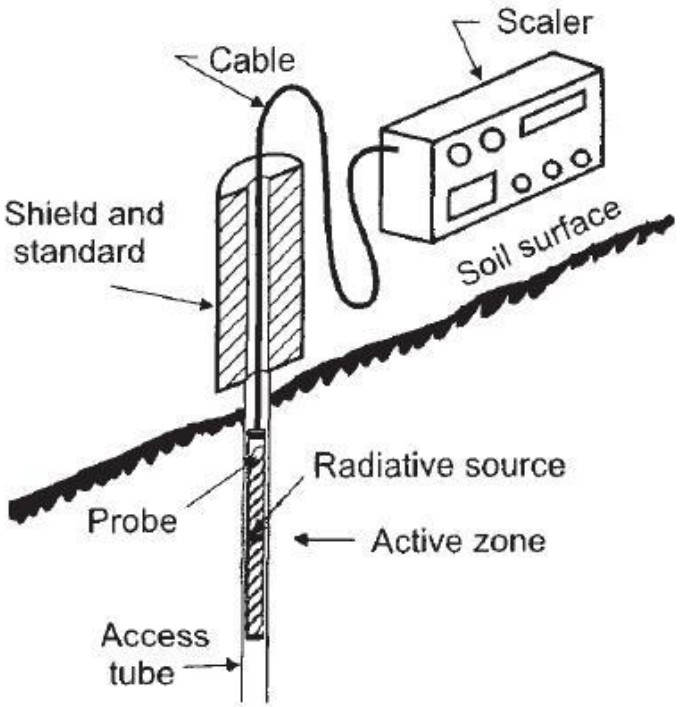


Fig. 6.3. Components of a portable neutron soil-moisture meter, including a probe (with a source of fast neutrons and a detector of slow neutrons) lowered from a shield containing hydrogenous material (e.g., paraffin, polyethylene, etc.) into the soil via an access tube. A scaler-rate meter is shown alongside the probe. Recent models incorporate the scaler into the shield body and the integrated unit is light-weight for easy portability.

Why such a success? A brief historical overview

Effect of soil moisture/snow on "natural" neutrons fluxes also known but considered **noise**

Physicists (Hendrick and Edge, 1966): the effect of soil moisture on cosmic ray neutron intensity above the ground surface was identified in measurements made over four decades ago but was considered **noise** in the measurement of neutrons.

Rock dating community (Gosse and Phillips 2001): several papers where soil moisture and other hydrogen pools are mentioned as **noise**

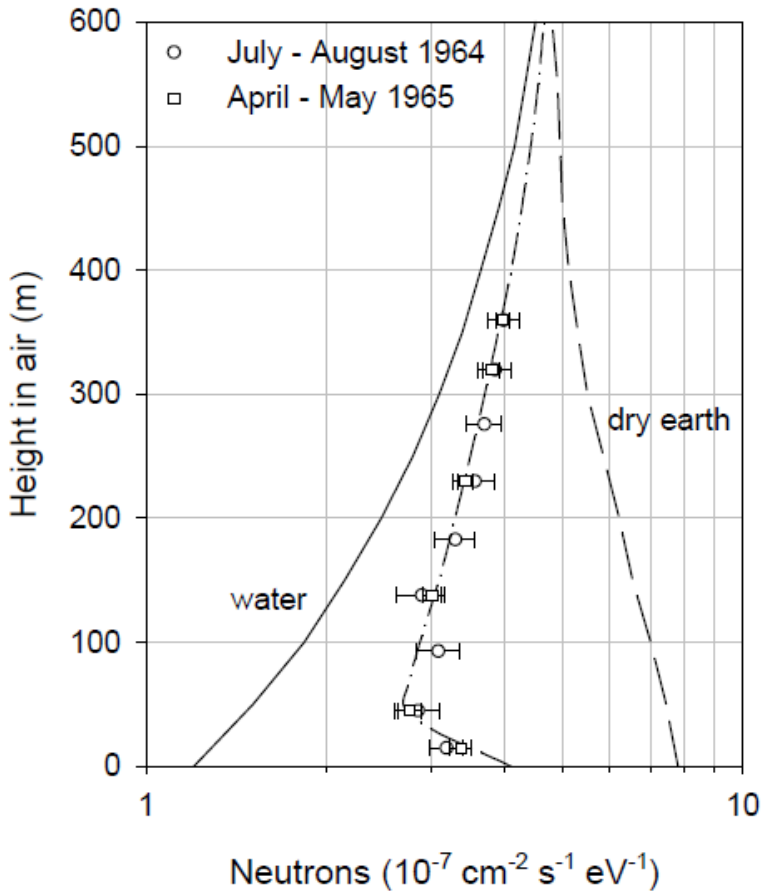


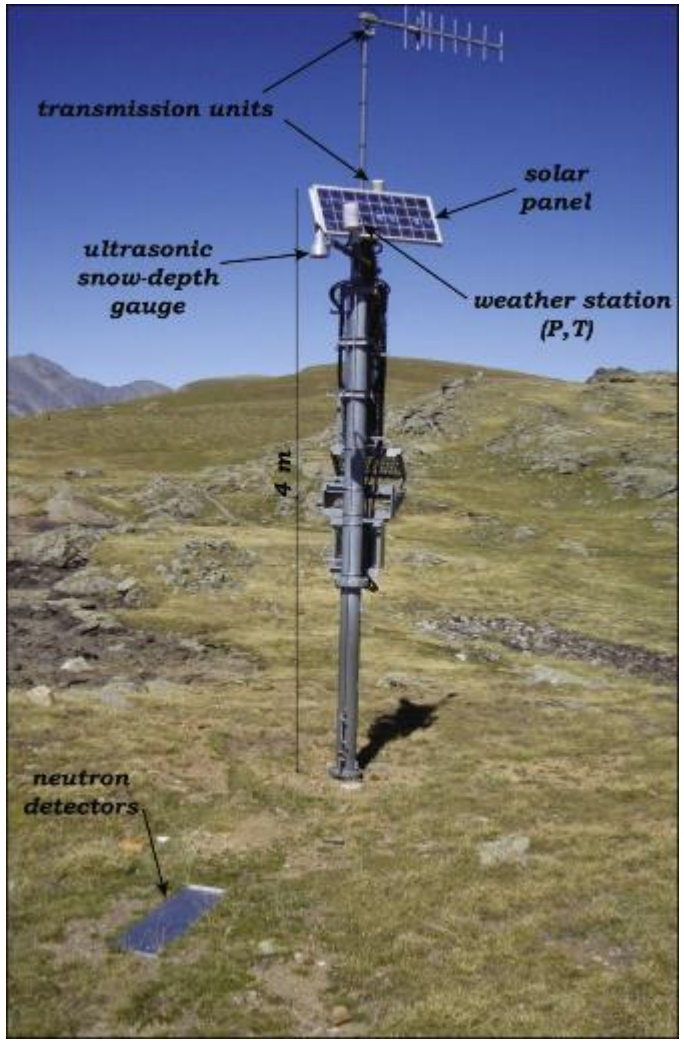
Fig. 2. Distribution of "fast" neutrons above the Earth's surface showing strong dependence on surface moisture. Circles and squares are measurements on a radio tower. A theoretical model that best fits the data (dash-dotted line) suggests a soil moisture of $0.03\,m^3\,m^{-3}$ to $0.05\,m^3\,m^{-3}$. Replotted from Hendrick and Edge (1966).

The “noise” used in hydrology

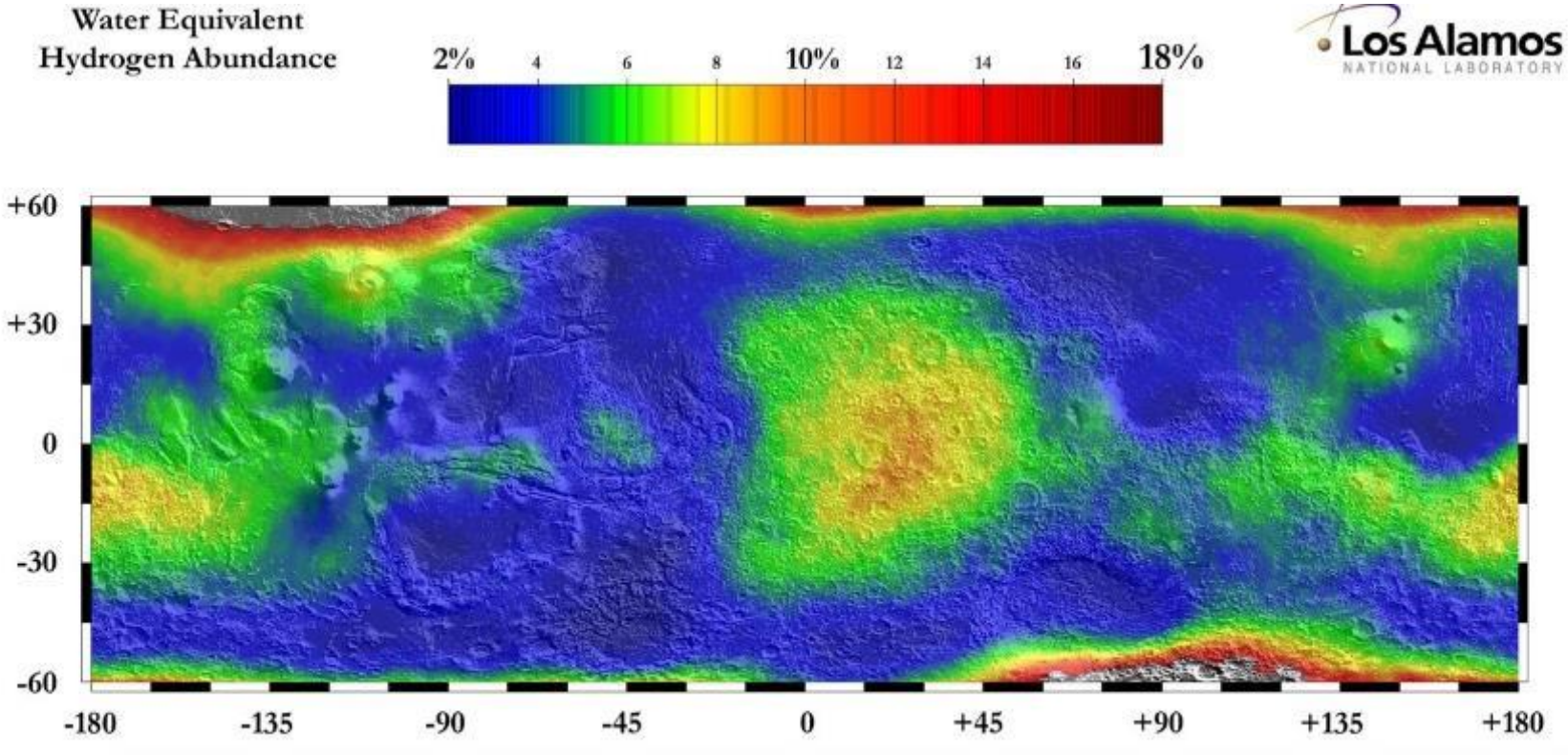
This “noise/signal” has been used in experimental hydrology

Kodama et al. (1979), Kodama et al. (1985): Cosmic-ray neutron measurements to the determination of the snow-water equivalent and soil moisture

Morin et al. (2012): Monitoring network in France An 18-yr long (1993–2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m alt.) for driving and evaluating snowpack models



And not only…looking at space exploration (Mars)



Mitrofanov, I., A. Malakhov, B. Bakhtin, D. Golovin, A. Kozyrev, M. Litvak, M. Mokrousov, et al. "Fine Resolution Epithermal Neutron Detector (FREND) Onboard the ExoMars Trace Gas Orbiter." *Space Science Reviews* 214, no. 5 (July 11, 2018): 86. https://doi.org/10.1007/s11214-018-0522-5.

Mass percents of water were determined from epithermal neutron counting rates using the Neutron Spectrometer aboard Mars Odyssey between **(2002-2003)**.

https://www.nasa.gov/vision/universe/solarsystem/new_maps_mars_water.html

Why such a success? A brief historical development

(~1950)
Neutron probe for soil moisture estimation but **active radiation source**

Hendrick and Edge (1966): the effect of soil moisture on **cosmic ray neutron** intensity above the ground surface was identified in measurements made over four decades ago but was considered **noise** in the measurement of neutrons.

Kodama et al. (1979), Kodama et al. (1985): Cosmic-ray neutron measurements to the determination of the snow-water equivalent and soil moisture (**installation below ground, small footprint**)

2003-present
Mars exploration with neutron sensors

Zreda et al.(2008); **Desilets et al.(2010):** Installation **above ground, large footprint**.

Why such a success after Zreda et al?

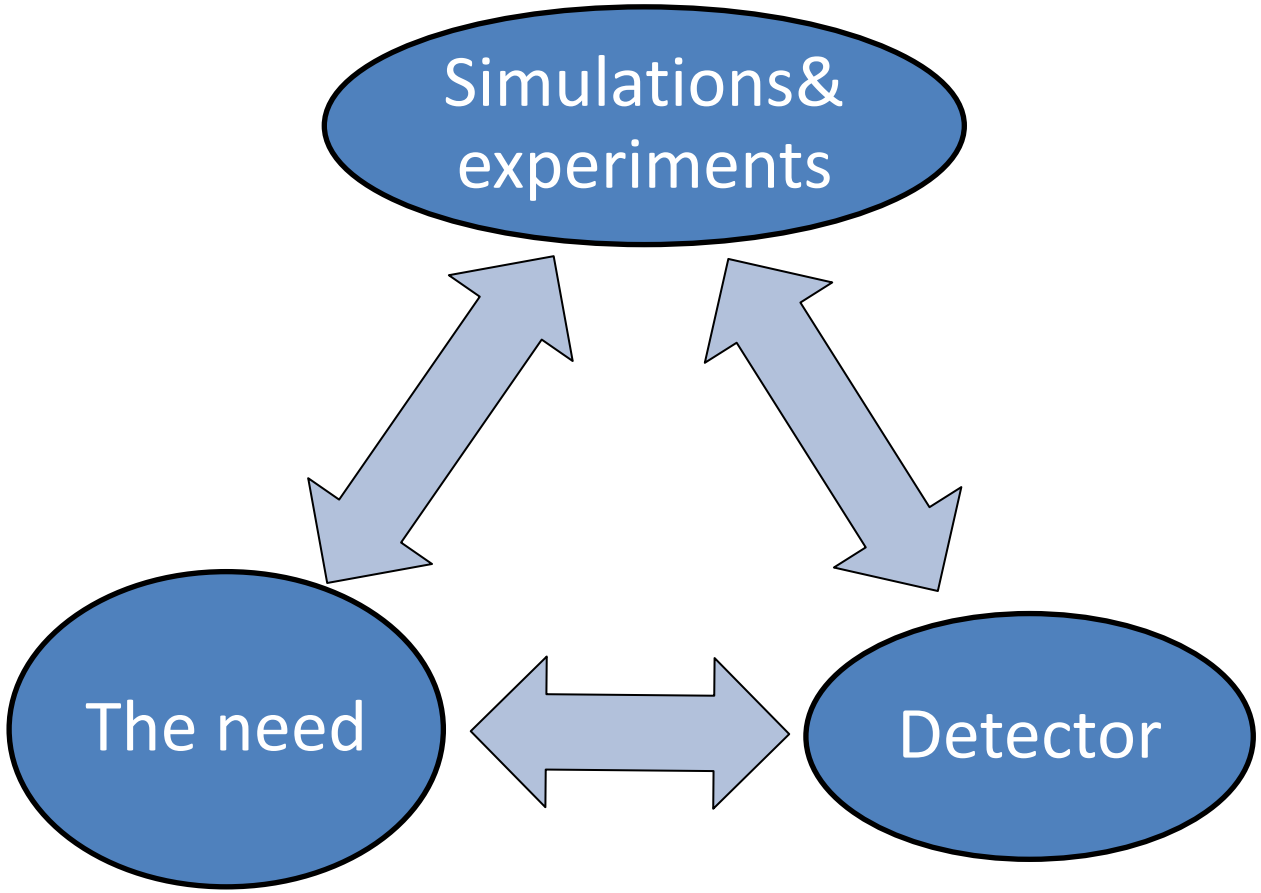
All the pieces of CRNS were there since long time but nobody merged them nicely

Three main factors

1. To know **the need** of intermediate scale soil moisture

2. **To quantify** and better understand the signal based on experiments and simulations

3. To provide a **simple commercial detector** for hydrological applications



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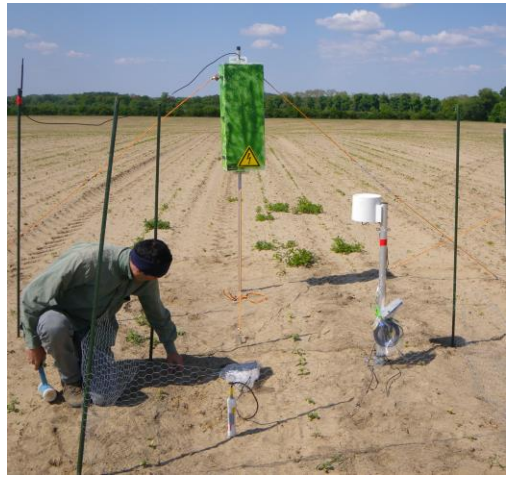
Where do I/we stand with CRNS?









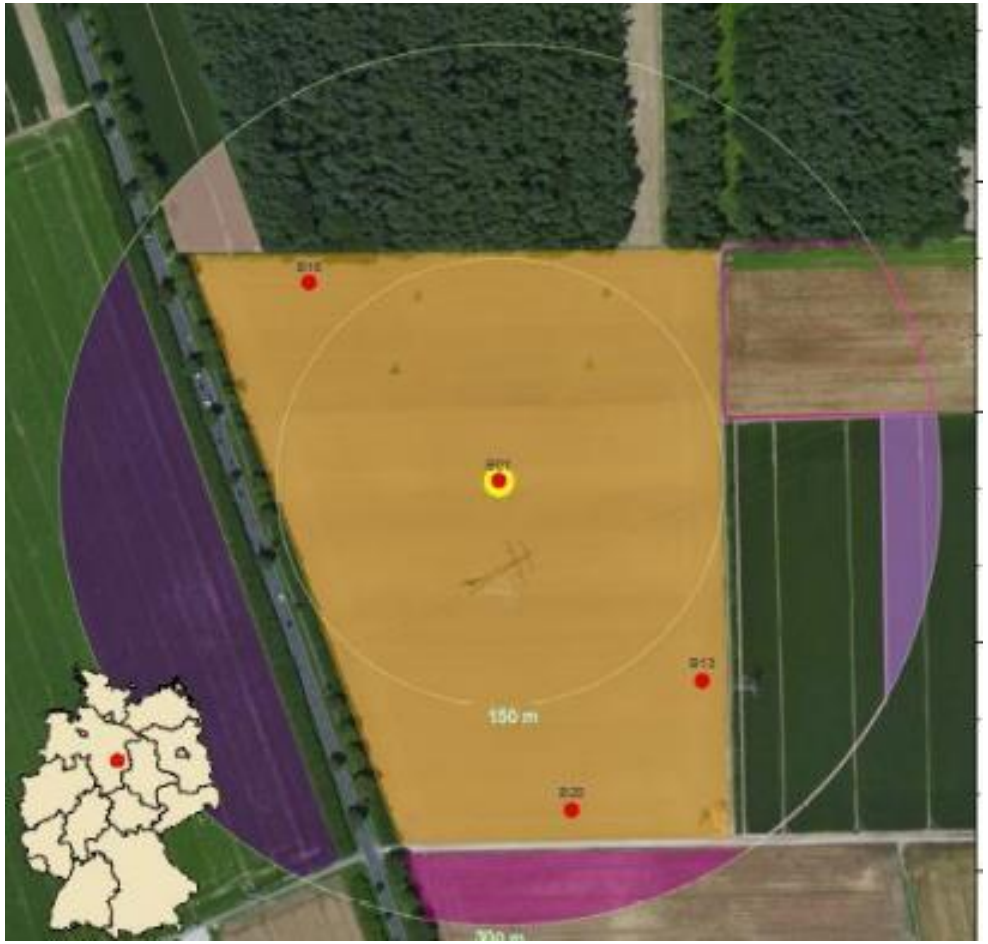
CRNS ten years old now

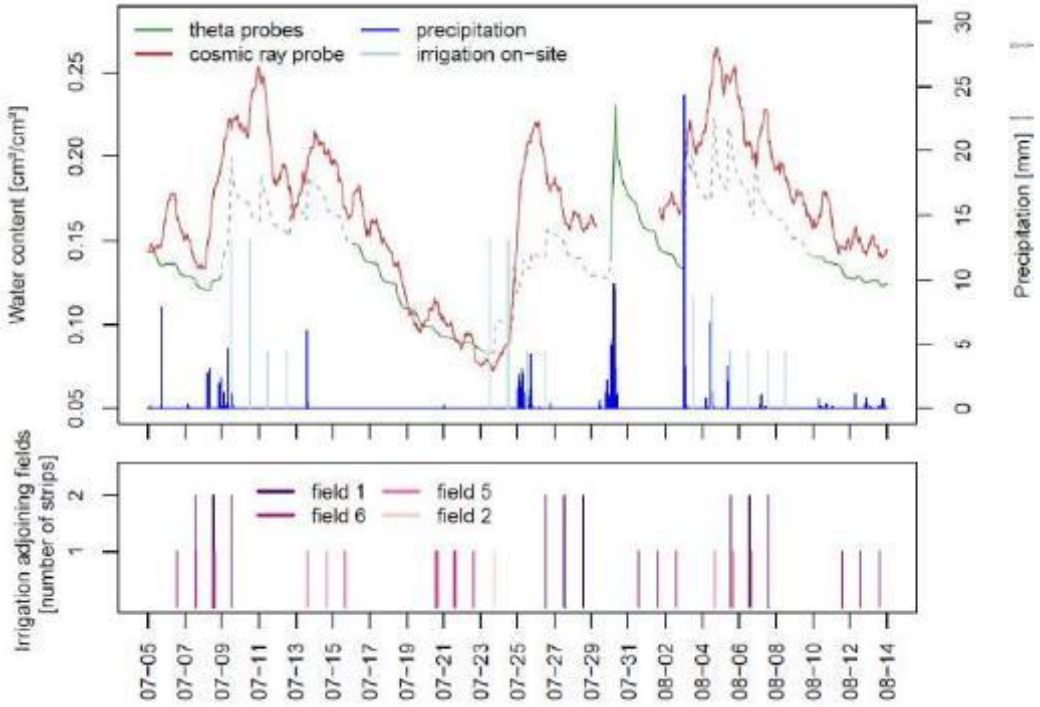
- Many tests conducted at different environmental conditions
- Many simulations
- Many groups and studies

General conclusions

- CRNS provides good results for soil moisture estimation for many applications
- CRNS is used also for snow observations
- If you need non-invasive intermediate scale soil moisture….go for it!

Fixed detector for, e.g., irrigation scheduling





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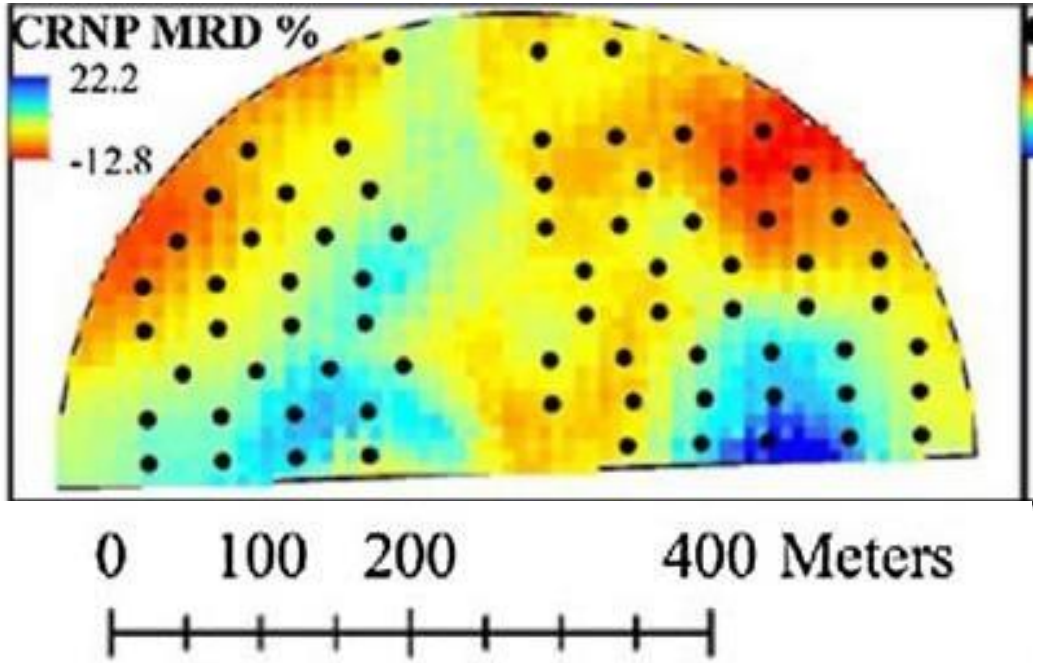
Rover for mapping



T.Franz (Nebraska)

Burdette Barkera et al. (2017)

What's next?

Some interesting research questions…

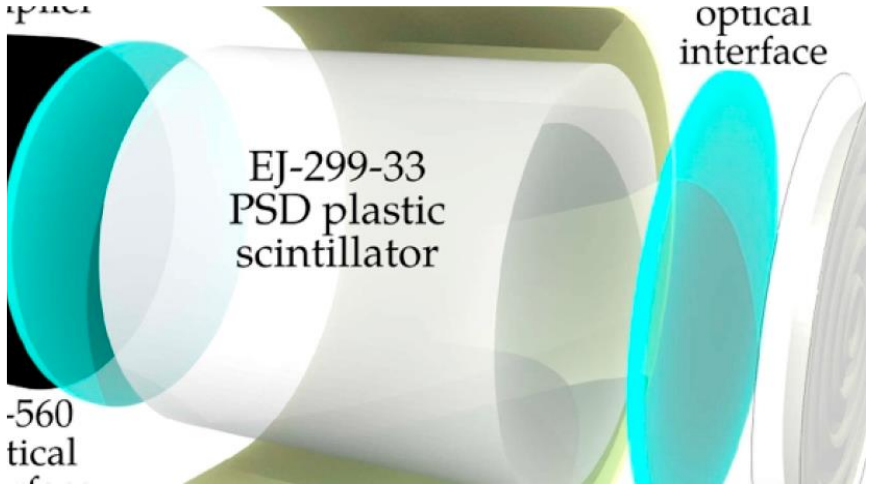
Searching for **alternatives commercial detectors** Why?: availability, lower costs, higher sensitivity, dimensions, etc. (Peerani et al., 2012)

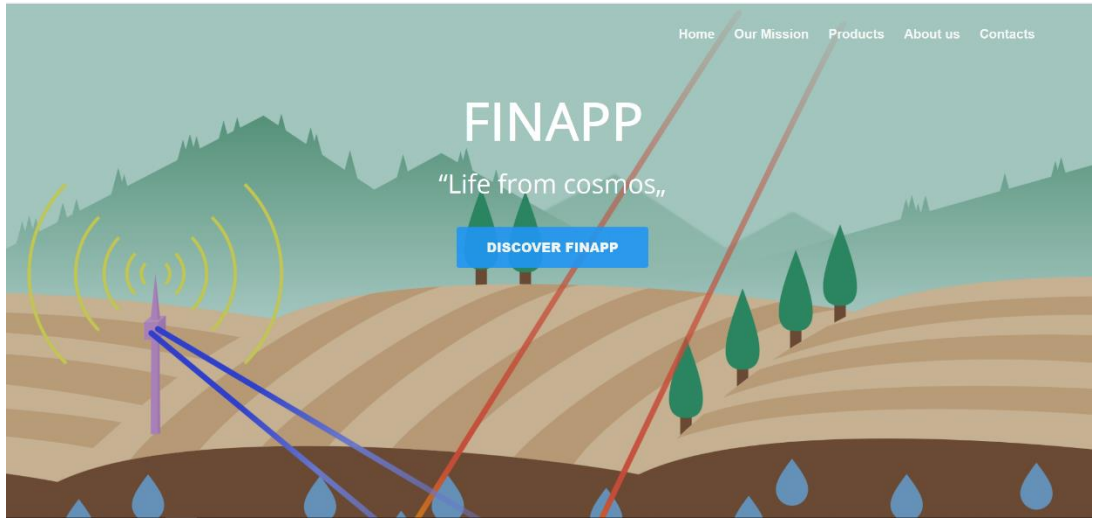
- Hydroinnova – USA (Darin Desilets): http://hydroinnova.com/main.html

- LabC (Marek Zreda, USA): http://lab-c.co/products/
- Styx-neutronica (Markus Köhli, Germany): https://www.styx-neutronica.de/
- FINAPP (Luca Stevanato, Padova – Italy): https://www.finapptech.com/

FINAPP, a new CRNS detector

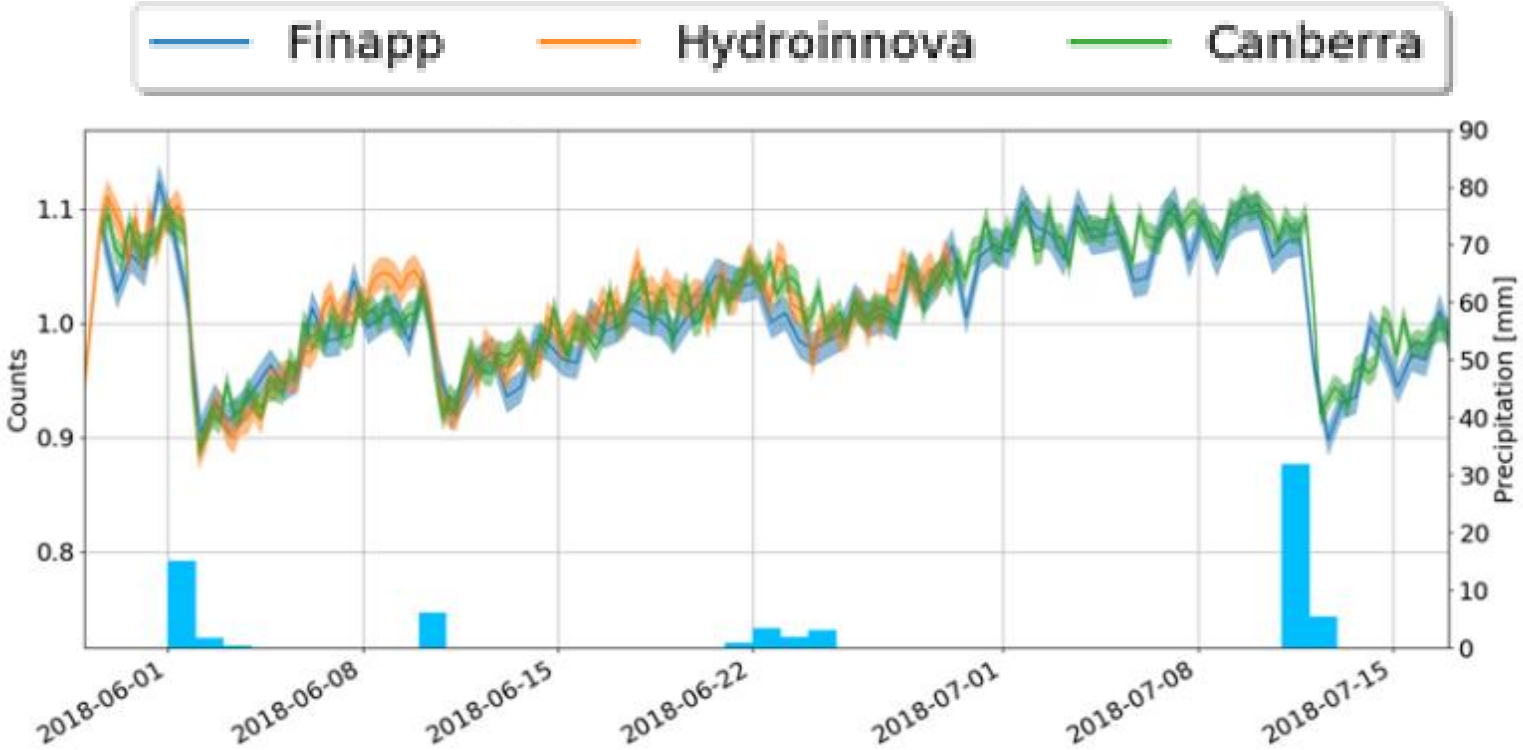
- **In 2016 I started collaborating** with Luca Stevanato and Marcello Lunardon, from University of Padova (IT)
- Neutron detectors for **homeland security** based on scintillators (Casper et al., 2016)
- What about using it for **agro-hydrological applications**?





- 2018: They founded a Start up: https://www.finapptech.com
- To develop **a competitive detector to current alternatives soil moisture probes** (e.g., drill&drop): lower costs, lighter detector, simple use plug&play

First results by Stevanato et al. (2019)



- **CRNS-FINAPP well performed** in comparison to current commercial CRNS probes
- Additional capability of detecting **muons and gammas.** Under studies the added value (paper in preparation by Stevanato et al.)

The detector is now undergoing some optimizations in the electronics and energy supply….new tests and results to come (hoping in safety conditions for travelling and work!)

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Collaboration with IAEA (Vienna – Austria)

IAEA
International Atomic Energy Agency

Coordinate research program (CRP)

New CRP: Enhancing Agricultural Resilience and Water Security Using Cosmic Ray Neutron Sensor (D12014)

New Coordinated Research Project

Emil Fulajtar, IAEA Department of Nuclear Sciences and Applications
Lee Kheng Heng, IAEA Department of Nuclear Sciences and Applications

APR
11
2019

Related Resources

- Coordinated Research Activities
- How to participate
- Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture
- Soil and Water Management and Crop Nutrition Section

- Supporting the use of CRNS for soil moisture and agriculture
- Develop and testing also gamma-ray spectrometer

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Outlook (1) for users

- Non-invasive proximal sensing methods are indirect measurements (**estimation**) as the point-scale soil moisture observations are

- **Several proximal sensing methods are emerging** and good opportunities in many applications as for agriculture

- Among others, **cosmic-ray neutron sensing is a mature methods** that reached the capability to be implemented for supporting e.g., agricultural water management

    - As a **fixed detector** for soil moisture dynamics (irrigation scheduling)
    - As a **rover** for precision agriculture (prescription maps)

Outlook (2) for developers

Interdisciplinarity: I‘m not physicists but is ten years now I read papers about nuclear physics, astrophysics and Mars explorations

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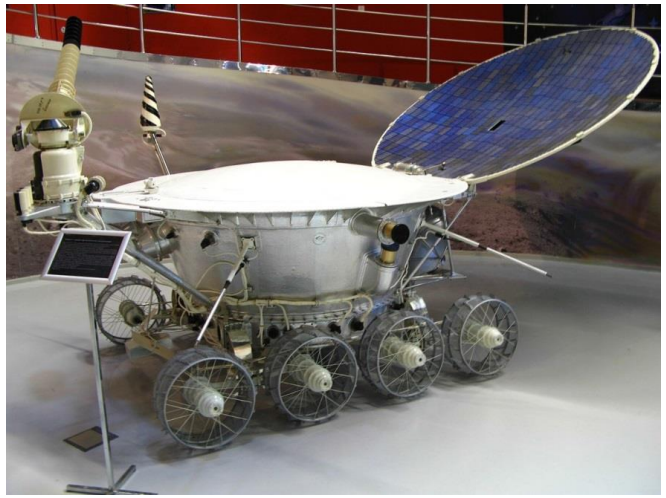
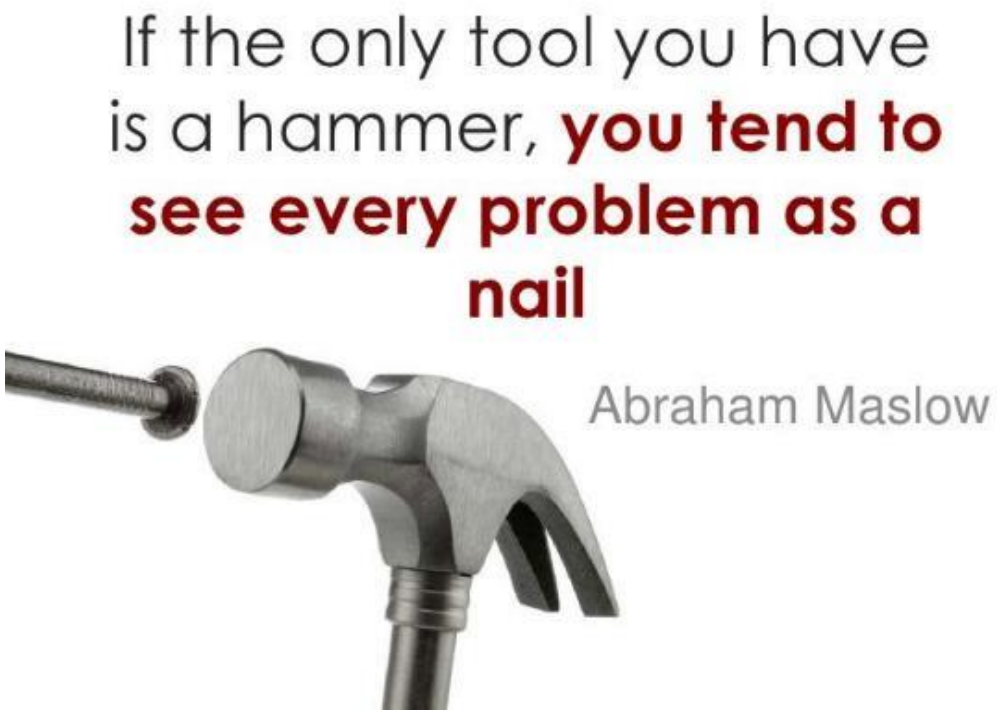


Lunokhod 1 (~moon walker in Russian) was the first astro-remote-controlled rovers landed on the Moon by the USSR November 17, **1970**

Rover for precision agriculture **(2020)**

Outlook (2) for developers

Transfer technology programs…Far to be a simple task!



References

Zreda, Marek, Darin Desilets, T. P. A. Ferré, and Russell L. Scott. "Measuring Soil Moisture Content Non-Invasively at Intermediate Spatial Scale Using Cosmic-Ray Neutrons." *Geophysical Research Letters* 35, no. 21 (November 1, 2008). https://doi.org/10.1029/2008GL035655.

Baroni, G., Scheiffele, L.M., Schrön, M., Ingwersen, J., Oswald, S.E., 2018. Uncertainty, sensitivity and improvements in soil moisture estimation with cosmic-ray neutron sensing. Journal of Hydrology 564, 873–887. https://doi.org/10.1016/j.jhydrol.2018.07.053

Stevanato, Luca, Gabriele Baroni, Yafit Cohen, Fontana Cristiano Lino, Simone Gatto, Marcello Lunardon, Francesco Marinello, Sandra Moretto, and Luca Morselli. "A Novel Cosmic-Ray Neutron Sensor for Soil Moisture Estimation over Large Areas." *Agriculture* 9, no. 9 (September 2019): 202. https://doi.org/10.3390/agriculture9090202.

Stevanato, L., M. Polo, M. Lunardon, F. Marinello, S. Moretto, and G. Baroni. "Towards the Optimization of a Scintillator-Based Neutron Detector for Large Non-Invasive Soil Moisture Estimation." In *2020 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*, 196–200, 2020. https://doi.org/10.1109/MetroAgriFor50201.2020.9277582.

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Thank you for the attention

Prof. Gabriele Baroni
Department of Agricultural and Food Sciences
Alma Mater Studiorum University of Bologna (Italy)
g.baroni@unibo.it