IAEA-TECDOC-1809

IAEA TECDOC SERIES

IAEA-TECDOC-1809

# Cosmic Ray Neutron Sensing: Use, Calibration and Validation for Soil Moisture Estimation

Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

IAEA
International Atomic Energy Agency

# COSMIC RAY NEUTRON SENSING: USE, CALIBRATION AND VALIDATION FOR SOIL MOISTURE ESTIMATION

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world''.

IAEA-TECDOC-1809

# COSMIC RAY NEUTRON SENSING: USE, CALIBRATION AND VALIDATION FOR SOIL MOISTURE ESTIMATION

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

For further information on this publication, please contact:

Soil and Water Management and Crop Nutrition Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org




Printed by the IAEA in Austria
March 2017

**IAEA Library Cataloguing in Publication Data**

Names: International Atomic Energy Agency.
Title: Cosmic ray neutron sensing : use, calibration and validation for soil moisture estimation / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2017. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1809 | Includes bibliographical references.
Identifiers: IAEAL 17-01080 | ISBN 978–92–0–101017–9 (paperback : alk. paper)
Subjects: LCSH: Soil moisture — Measurement. | Cosmic ray neutrons. | Agricultural innovations..

# FOREWORD

The IAEA and the Food and Agriculture Organization of the United Nations, through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, assist scientists and farmers worldwide to ensure food security and to promote sustainable agricultural resources. The Joint Division's programme and activities are demand driven, and focus on developing and transferring technologies in response to practical needs. The programme provides assistance to Member States in the implementation of suitable nuclear and related techniques, where these have a competitive advantage to enhance, improve or increase agricultural production.

This publication was developed as a practical guide for the use of the cosmic ray neutron sensor (CRNS), a new soil moisture sensing technology. The publication aims to provide an introduction to the technique, an explanation of its utility, and a description of standard operating procedures and data processing, including calibration and validation. The CRNS is a novel and unique technology, and standardized procedures for its use have been developed and published by academic research institutions. This publication can be used as a reference guide for Member States wishing to utilize this technology.

The IAEA wishes to thank all contributors to its Soil and Water Management and Crop Nutrition Subprogramme, in particular, the University of Nebraska–Lincoln and HydroInnova (United States of America), the Technische Universität Wien and the Federal Agency of Water Management (Austria), and to the contributors to the preparation of this publication. The IAEA officers responsible for this publication were A. Wahbi, G. Dercon and L. Heng of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

## CONTENTS

## SUMMARY

To meet the nutritional demand of the 21st century, global agricultural output must be increased. This will put pressure on already strained surface and groundwater resources. The incorporation of new techniques and technologies into agricultural resource management has the potential to improve the ability of farmers, scientists, and policy makers in assuring food security. The Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division, focuses on the development of improved soil, water, and crop management technologies and practices for sustainable agricultural intensification through the use of nuclear and conventional techniques.

Nuclear and related techniques can help develop climate-smart agricultural practices by optimizing water use efficiency. The measurement of soil water content is essential to improve the use of this resource in agriculture. However, most sensors monitor small areas (less than 1 m in radius), hence a large number of sensors are needed to obtain an area-averaged representation of soil water content which can be both costly and labor intensive. Wider scale measuring devices are needed as an alternative to the traditional, point approach. The cosmic ray soil neutron sensor (CRNS) is such a device that monitors soil water content in a non-invasive, non-hazardous, and continuous way. This recently developed device is used to measure water content in the topsoil over wide areas, covering up to 30 hectares. It fills the gap in measuring soil moisture over large areas for better agricultural water management.

A CRNS can be used to monitor soil water content over a footprint (the area covered by the sensor) diameter of 600 m (approximately 30 hectares in area) and to an integrated depth varying from 0.1 to 0.6 m, depending on soil water content. The cosmic ray technique is a fairly recent advance soil moisture monitoring technology, having developed out of research performed mainly over the past decade. The technique is applicable to a number of disciplines, including ecology, agronomy, atmospheric science, and remote sensing which require a robust, readily deployable field instrument for automatic monitoring of near surface and area wide moisture conditions. These applications take advantage of the large footprint, which provides spatial representativeness, and the non-invasive nature of the sensor, which facilitates installation and avoids disturbing the hydrologic properties of the soil being measured.

This publication was developed as a partial output of the Coordinated Research Project titled: “Landscape Salinity and Water Management for Improving Water Productivity” managed by the Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division. This publication is intended to serve as a guideline for scientists, technicians, and students and provides a description of the key characteristics of the technique, a review of recent literature related to its use and field validation, and procedures for installation, calibration, and validation. The data processing procedure is also described and includes corrections based on ancillary measurements of air temperature, relative humidity, and barometric pressure as well as corrections derived from publically available data of solar activity.

This publication is divided into three Chapters. Chapter one provides an introduction to the technique and the physical principles behind its function. It also illustrates the theory and parameters to be considered as well as the associated calculations and calibrations; Chapter two details the appropriate field installation procedures for a general CRNS device and the associated materials; Chapter three provides a step-by-step instruction on field calibration and validation procedures related to the use of the CRNS. Additionally, examples of validation campaigns performed by multiple academic research institutions are provided to demonstrate different validation techniques.

Future research and publications will include a validation of the CRNS footprint and its applicability in alpine environments as well as a determination of the impact of agricultural crop water content on the CRNS signal. To aid the readers and users of the CRNS, this publication is supplemented by an Excel spreadsheet on the attached CD-ROM which illustrates the transformation of raw CRNS data into calibrated volumetric water content including a correction using weather data.

*The IAEA does not endorse the product mentioned in the publication. D. Desilets, co-author of this publication, is co-owner of HydroInnova LLC which manufactures the CRNS used in this study as a test case. His contributions are provided as an expert in this field of study and the remaining authors declare that there is no conflict of interest regarding the publication of this manuscript. The information provided is relevant for any CRNS device.*

# CHAPTER 1. OVERVIEW OF THE COSMIC RAY TECHNIQUE INCLUDING MEASUREMENT PRINCIPLES AND CALCULATIONS

D. DESILETS
HydroInnova LLC,
Albuquerque, New Mexico USA

## 1.1. INTRODUCTION

The cosmic ray method provides a non-contact way to independently and continuously monitor water content in the upper layers of soil. With the cosmic ray method, one obtains spatial average soil moisture over a large lateral radius, approximately 260 m at sea level, providing an unprecedented scale of observation. The sample depth is integrated over the top several decimetres of soil; or, in winter, the water equivalent depth of snow up to 15 cm. The cosmic ray method is perhaps the most robust near field method for automatically observing land surface water, including soil moisture.

The instrument, called a cosmic ray soil neutron sensor (CRNS), utilizes naturally occurring cosmic ray neutrons as a proxy for soil water content. The intensity of natural neutrons is inversely proportional to the amount of water present near the land surface. A data logger records neutron intensity from a sensor located in a weatherproof enclosure located a meter or so above the ground. The data logger also records barometric pressure, temperature and relative humidity from additional sensors. Data from the additional sensors are used for corrections to the neutron counting rate. Other meteorological and hydrological sensors can also be added (recommended) to the data logger to supplement the soil moisture observations.

The neutron detectors, data logger and pressure sensor are housed in a sturdy outdoor rated aluminium enclosure, while temperature and relative humidity sensors (recommend to include a rain gauge) are mounted externally. Power is fed to a charge controller and deep cycle battery house in the enclosure through a cable grip located at the bottom of the enclosure. A breather vent is used to equilibrate barometric pressure inside of the enclosure with the pressure outside of the enclosure.

An algorithm for converting neutron counting rates (raw data) to soil water content is included in this protocol (Excel spreadsheet contained on the CD-ROM included in this publication). The algorithm requires at least one calibration parameter, which can be determined by cross-calibrating one sensor against an already calibrated sensor or by performing the field calibration described in this publication. The main objective of calibration is to determine the theoretical dry soil counting rate for a particular site, which serves as a reference counting rate for subsequent measurements.

Data can be retrieved remotely in one of three ways: via an internal *Iridium* satellite modem, an internal GSM modem, or external GSM pass-through modem connected to a serial port on the CRNS data logger. Low cost data telemetry is facilitated by low data rates, typically less than ten bytes per hour. Other telemetry options can be implemented.

## 1.2. APPLICATIONS OF SOIL MOISTURE MONITORING

Near surface soil moisture (i.e. that in the top meter of soil) impacts many aspects of human life through its effects on vegetation, surface runoff, aquifer recharge, hill slope stability and land surface interactions with the atmosphere. Soil moisture is crucial to agriculture, where sufficient water is crucial to support germination and plant growth during critical parts of the growing season. Information on soil water content, determined directly from soil measurements or indirectly from plant health, is used by farmers in water deficient climates to schedule irrigation applications. Soil moisture is a key determinant of yields, through its effects on germination, nutrient availability and plant growth.

Where soil moisture has been in prolonged deficit, the result is drought and desertification, with attendant ecological damage. On the other hand an excess of soil moisture, particularly in the shallow top layers of soil, is a major factor in the occurrence of surface runoff and even catastrophic floods. Furthermore, excess soil moisture is detrimental to plant roots. In areas where topographic and geologic factors combine, soil water can produce hill slope instability by weakening the cohesion of soil particles and by increasing the mass of overburden to the point where destructive landslides and debris flows can be triggered. Furthermore, the role of soil moisture in climate and weather and its complicated feedbacks are being increasingly appreciated due to advances in land surface modelling. Soil moisture is a major control on energy and water exchanges between the land and atmosphere, with profound consequences for summer convective precipitation in particular.

Although many impacts are widely appreciated, as a practical matter soil moisture has been notoriously difficult to measure at the scales needed to address problems in agriculture, drought monitoring, hill slope stability, and numerical atmospheric modelling. The problem has been twofold; one is a lack of methods operating at the scale of interest (generally the measurement scale is too small); the other is the difficulty in inferring the broader moisture field from small scale measurements. The problem with small scale measurements is that soils tend to be heterogeneous; hydraulic parameters in particular can vary naturally by orders of magnitude over distances of meters. There is promise that the gap in measurement scales can be filled by new technologies, such as the CRNS, that provide a wider and more spatially representative sample area.

### 1.2.1. Moisture monitoring techniques: The state of the art

A detailed review of soil moisture monitoring techniques is covered by the IAEA publication TCS30, Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, And Sensor Technology [1]. That publication describes the following approaches:

(a) Direct gravimetric/volumetric determinations;

(b) Time domain reflectometry;

(c) Frequency domain reflectometry;

(d) Tensiometer;

(e) Electrical resistance sensors;

(f) Neutron soil moisture meters.

At the time of that report, the CRNS was new and not widely known. However, the physical principles underlying this emerging method had actually been familiar to soil scientists for several decades. The cosmic ray technique is a natural neutron scattering method, and like the conventional neutron moisture meter, relies on the unique ability of hydrogen to slow down neutrons. The publication [1] concluded that the field calibrated neutron moisture meter "remains the most accurate and precise method for soil profile water content determination in the field, and is the only indirect method capable of providing accurate soil water balance data for studies of crop water use, water use efficiency, irrigation efficiency and irrigation water use efficiency..." In this connection, it is worth pointing out that several of the advantages of the neutron moisture meter, particularly its insensitivity to soil texture, are common to the CRNS. There are also important differences. Foremost are that the CRNS entails longer integration times and is restricted to shallower depths, but is less sensitive to soil chemistry, completely passive (no radioactive source), noninvasive, and represents an area several orders of magnitude larger than other soil moisture sensing techniques, and therefore can provide more representative soil moisture values than the conventional neutron moisture meter.

A key distinction between the CRNS and nearly all conventional field techniques, including the neutron moisture meter, is the sample area. Cosmic ray neutrons are spatially distributed and can scatter large distances in air. This characteristic gives the sensor a footprint on the order of hundreds of meters [2]. By contrast, a soil neutron moisture meter utilizes a point source, and measures neutrons backscattered entirely within the soil, giving it a sample radius on the order of 15 to 50 centimetres. In general, most conventional sensors measure a volume even smaller than this, and in consequence require a large number of sensors in order to obtain a spatially representative field sample.

### 1.2.2. Measurement principles

#### *1.2.2.1. Theory*

As a natural component of Earth's radiation environment, cosmic ray neutrons are ever present at the land surface. These neutrons are cosmic only in the sense that they are a byproduct of chain reactions initiated at the top of the atmosphere by cosmic rays. The initiating cosmic ray particles, known as primary cosmic rays, consist mainly of highly energetic protons and helium nuclei which originate in supernovas throughout the Milky Way. Upon reaching the atmosphere, a primary cosmic ray collides with air molecules, causing their nuclei to explode into a shower of protons, neutrons and other subatomic particles. These fragments rain down upon Earth, initiating new interactions as they traverse the atmosphere. Hence the radiation propagates as a cascade (Fig. 1.1). As this chain reaction progresses, the energy of the primary particle becomes spread among a growing number of secondary particles; consequently, the average energy per cascade particle is greatly diminished with depth. Eventually, the chain reaction can no longer propagate itself effectively, and the radiation attenuates with depth in the atmosphere at an exponential rate. Fast neutrons are generated by cascade particles as they interact with nuclei in the atmosphere and upper few meters of the Earth's crust [3].

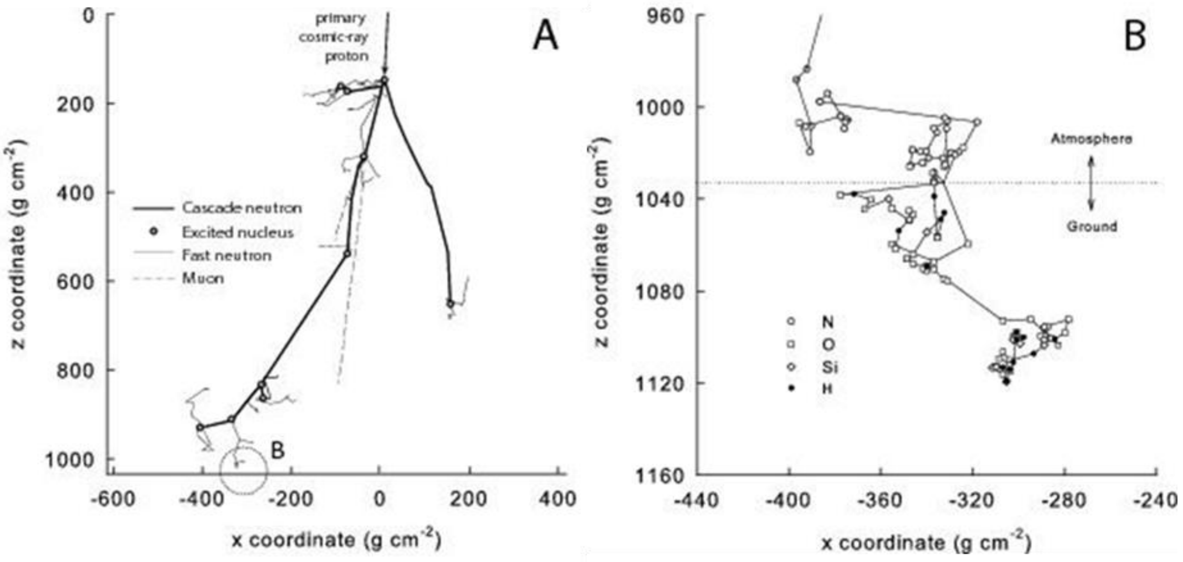


*Fig. 1.1. (A) Atmospheric particle cascade simulated with the radiation transport code Monte Carlo N-Particle eXtended (MCNPX). A 10 GeV primary cosmic ray proton collides with atmospheric nitrogen, triggering a particle cascade that reaches sea level. Fast neutrons are generated at each collision marked by a circle. Particle tracks are shown for energies above 1 MeV. (B) A fast neutron generated by the cascade near the land surface (circled in Fig. 1.1A) is scattered in random directions as it is moderated and eventually captured in the ground. As shown in [3].*

Fast neutrons observed at the land surface are mainly a product of the nuclear evaporation process — a process which is initiated by the cascade particles. When a weaker cascade particle collides with a terrestrial nucleus (e.g. Si, O, N nuclei), the nucleus may simply heat up rather than immediately bursting into fragments. The nucleus rapidly cools off by ejecting (evaporating) fast neutrons, in a process analogous to the evaporation of water molecules from a lake. Each of the fast neutrons is then scattered in random directions, losing energy through elastic collisions with air and soil nuclei. These fast neutrons will propagate the cascade no further. Eventually, following many tens of collisions, the neutron will lose most of its energy and will be captured by a nucleus in the air or soil. At this point the neutron ceases to exist as an unbound particle, and no longer contributes to the radiation environment.

The transmission of fast neutrons through soil is profoundly influenced by the presence of hydrogen, which at the land surface is mainly in the form of water. Hydrogen is unique in its ability to rapidly moderate (i.e. slow) neutrons — a consequence of the low mass and relatively large elastic scattering cross section (a measure of the size of the nucleus as seen by a fast neutron) of hydrogen. Because the two bodies have the same mass, a fast neutron can theoretically be brought to rest through a single head-on collision with hydrogen. The fewer the number of collisions needed to moderate a fast neutron, the lower the fast neutron intensity will be. Elastic collisions with hydrogen and other light nuclei progressively moderate the neutron until it is either captured by a nearby nucleus or slowed to equilibrium with the thermal motions of the surrounded medium.

Thermal neutrons have a strong tendency to be absorbed by certain nuclei. Common absorbing elements in soil include major elements such as Fe, Ca, K, and trace elements with unusually high absorption cross sections, such as B, Gd and Sm. This propensity toward absorption makes thermal neutron intensity sensitive to soil chemistry. The primary channel of a CRNS (called the mod channel; fast neutron count over the preceding time interval) responds to neutrons in the epithermal to fast regions, and to a large extent avoids any dependence on soil chemical composition, beyond H content. The mod channel is sometimes supplemented with a low energy counter (bare channel) which may be used to correct the mod channel, to infer quantities of water in the land surface environment other than soil water, and/or to augment the counting rate of the mod channel. In this last application the bare channel is simply be calibrated to the mod channel to provide better counting statistics. The bare counter is used frequently in research settings, whereas operational soil moisture networks tend to rely mainly on the mod channel.

#### *1.2.2.2. Radius of influence*

A unique characteristic of the cosmic ray technique is the large extent of the measurement area. This extent is determined by the distance a fast neutron tends to travel from where it is emitted from the ground to where it is detected by the sensor. If the energy sensitivity of the sensor is significantly lower than the energy of neutron emission (about 1–2 MeV for neutrons evaporated from nuclei following cosmic ray excitation [4]), the neutron is first moderated through numerous elastic collisions before it can be detected. For a neutron detected aboveground, many of those collisions inevitably take place in the air. Because the mean free path for collisions in air is on the order of 30–140 m (mean free path increases with energy), a random walk involving tens of elastic collisions in air can transport a fast neutron several hundred meters from where it was first emitted (Fig. 1.2). The average net displacement for a neutron, and therefore the radius of influence, increases as the separation increases between the initial energy and the detection energy, and as the collision mean free path increases.

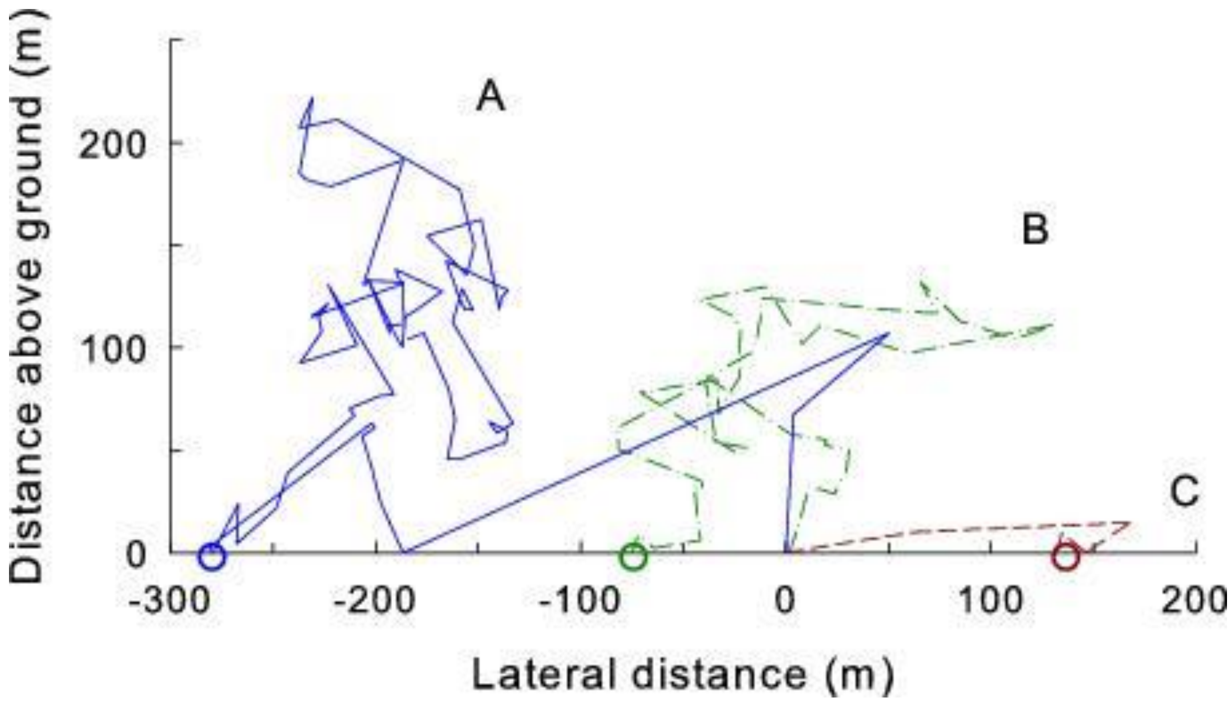


*Fig. 1.2. Three random walks simulated for particles emitted from the ground surface and detected within 2 meters of the ground.*

The net result of this scattering process is a radius of influence which can be defined in terms of an exponential function [5]:

$$\phi_0(r) = 1 - \exp\left(-\frac{r}{L}\right) \quad (1.1)$$

Here $\phi_0$ is the fraction of the neutron intensity that is derived from within radius *r*, and *L* is the exponential folding length. Note that by definition $\phi_0$ decreases by a factor of *e* (~2.718) for every distance *L*. In previous studies [5,6], the lateral radius of influence, *R*, was defined as being two exponential folding (attenuation) lengths, i.e.

$$R = 2L \quad (1.2)$$

By definition, *R* circumscribes the area responsible for contributing 86.5% of the recorded counts. Desilets et al. [5] found that *R* = 300 meters at sea level from Monte Carlo neutron transport simulations. The radius was found to be fairly insensitive to soil moisture and height of the detector above the ground for heights up to a few tens of meters, but decreases with atmospheric humidity and barometric pressure (i.e. increased atmospheric water content or density tend to keep neutrons from scattering as far in the atmosphere).

Recent work suggests that at sea level the footprint is about 12% lower than initially reported by [5] (Desilets, unpublished data). The more recent calculations followed the same methodology as before, except that average distance travelled by a neutron was calculated as a weighted average using weights that are optionally reported by the transport code. Certain variance reduction techniques employed by the code, apparently automatically, can cause particles to have unequal weights. The new investigation found that particles with longer track lengths tended to have lower reported weights, and as a consequence the weighted average tends to produce a lower footprint. However, all of the dependencies of the footprint, as well as the magnitudes of these dependences, found in the recent simulations confirm the results of Desilets et al. [5]. The updated radius of influence at sea level was found to be 264 m for dry soil in a dry atmosphere. This value is referred to as $R_0$, with the subscript indicating that the radius is referenced to the specified conditions. To calculate the radius of influence under any particular conditions the following correction factors can apply:

$$R = R_0 \cdot f_{\mathrm{hum}} \cdot f_{\mathrm{bar}} \tag{1.3}$$

where the first correction factor takes into account atmospheric humidity:

$$f_{\mathrm{hum}} = -7.763\mathrm{x}10^{6} \frac{H}{\rho_{air}} + 1 \tag{1.4}$$

where $\rho_{air}$ is atmospheric density (g cm$^{-3}$) and $H$ is absolute humidity, by convention in units of g m$^{-3}$ (see equations 1.13 and 1.14 for calculation of $H$ from meteorological data). Note that the coefficient in this equation includes the factor $10^6$ in order to adjust for the different volumetric units of $H$ and $\rho_{air}$.

The second factor takes into account atmospheric pressure $P$, and can be calculated as:

$$f_{\mathrm{bar}} = \frac{P_0}{P} \tag{1.5}$$

Pressures are usually reported in units of mb or hPa (although for this calculation the units do not matter since only the ratio of pressures is required).

The radius of influence is an important characteristic of the CRNS, and refined estimates of its functional form and numerical values will continue to be a critical research need. Recent work by Köhli et al. [7] suggests a double exponential model for the lateral footprint with a response much more heavily weighted to the first 10 m than found by Desilets et al. [5], although it is not clear if the definition of the footprint is consistent between the two works. Experiments and simulations have been underway to verify the physical possibility of the proposed double exponential model.

#### *1.2.2.3. Sample depth*

As with the radius of influence, the sample depth follows an exponential relation, such that

$$\phi_0(z) = 1 - \exp\left(-\frac{\rho_w z}{\lambda}\right) \tag{1.6}$$

where $\phi_0$ is the fraction of neutron intensity derived from a depth less than $z$ (cm), $\rho_w$ (g cm$^{-3}$) is the wet bulk density of the soil and λ (g cm$^{-2}$) is the penetration length. The sample region is again defined as including the source region for 86.5% of the detected neutrons, a distance equivalent to two penetration lengths. Results given by Zreda et al. [6] imply that the sample depth ranges from 12 cm for saturated soil to 76 cm for dry soil based on neutron transport simulations. These values have been more or less confirmed by the work of Köhli et al. [7], who report a sample depth between 15 cm and 83 cm for their simulated soils.

## 1.3. CALCULATIONS

### 1.3.1. Calibration function

A shape defining function can be used to convert neutron counting rates to soil water content for most silica dominated soils. This function is valid for neutrons in the epithermal to fast part of the spectrum ($10^0$–$10^6$ eV), where neutron absorption is negligible. A calibration curve for soil water content has been obtained by fitting simulated ground level neutron fluxes to the semi-empirical shape defining equation [5], which can be written in a more generalized form as

$$\theta_T = \theta_V + \theta_{LW} + \theta_{SOC} + \theta_B + \ldots + \theta_i = \left( \frac{a_0}{F(t)\frac{N}{N_0} - a_1} - a_2 \right) \rho_b \quad (1.7)$$

where

$a_0 = 0.0869$
$a_1 = 0.3720$
$a_2 = 0.1236$

and

$\theta_T$ (cm$^3$ cm$^{-3}$) is the total volumetric water content. This total consists of soil water content $\theta_V$ (the main variable of interest), clay lattice water content $\theta_{LW}$, the soil organic carbon water equivalent $\theta_{SOC}$, and the biomass water equivalent $\theta_B$ all in volumetric units (cm$^3$ cm$^{-3}$). The term '$+\ldots+\theta_i$' allows for the inclusion of other pools of hydrogen which might be present; generally this term is assumed to be zero, but future research may discover new terms to be included here. As a matter of algebraic manipulation, these volumetric quantities can be expressed in gravimetric units by simply multiplying their values by the soil bulk density, $\rho_b$ (g cm$^{-3}$).

On the far right side of the equation, $N$ is the raw neutron counting rate, $N_0$ is the theoretical dry counting rate. The correction factor *F(t)* accounts for variations in barometric pressure, solar activity and absolute humidity (weather parameters), as explained below. These three variables have in common that they change in time, in accordance with changing meteorological and space weather conditions.

The parameters $a_0$, $a_1$ and $a_2$ define the shape of the calibration function. The numerical values have been determined using neutron transport simulations and a best fit procedure, as reported by Desilets et al. [5]. Unfortunately, the coefficients given in that work were specified with the caveat that they are only valid down to 0.02 kg kg$^{-1}$. It has recently become apparent that this limitation is artificial—an artefact of the best fit procedure used by Desilets et al., and is not a deficiency inherent in the form of equation 1.7. The limitation has been eliminated, with no loss of accuracy, by adjusting the coefficients originally reported by Desilets et al. This adjustment has two effects. One is to extend the range of calibrated water contents to their natural limit, 0.00 kg kg$^{-1}$. The other, mainly academic, is that $N_0$ is now truly defined as the dry counting rate (whereas the previous coefficients implied a small amount of residual water in theoretical dry soil). The adjusted coefficients are reported following equation 7.

The general procedure is to first calculate the dry counting rate ($N_0$) from the gravimetric soil sampling and corrected neutron count. Then calculate the corrected neutron intensity, the total water content, and finally subtract unwanted components of the total water content to arrive at the pore soil water content (volumetric water content).

The total correction factor $F(t)$ can be decomposed into the product of several specific correction factors (Table 1.1, column 11),

$$F(t) = f_{\mathrm{bar}} \cdot f_{\mathrm{sol}} \cdot f_{\mathrm{hum}} \cdot \ldots \cdot f_i \qquad (1.8)$$

The first of these is the barometric pressure correction factor, calculated as (Table 1.1, column 6)

$$f_{\mathrm{bar}} = \exp\left[\beta\left(P(t) - P_0\right)\right] \qquad (1.9)$$

where $P(t)$ is the barometric pressure recorded at the site in hPa, $P_0$ is a fixed reference pressure in hPa, usually taken to be an approximate long term average for the site, or calculated from the elevation and a model representation of the atmosphere. $\beta$ is the pressure coefficient, which at high to mid latitude can be assumed to be 0.0077 hPa$^{-1}$. For lower latitudes $\beta$ can be calculated from formulas given in [8].

The second factor corrects for variations in solar activity, and is calculated as (Table 1.1, column 10)

$$f_{\mathrm{sol}} = \frac{M_0}{M(t)} \qquad (1.10)$$

where $M(t)$ is the counting rate of a neutron monitor at time $t$, and $M_0$ is the counting rate at an arbitrarily chosen reference time. (The idea is to normalize all counting rates to a single reference solar activity level; the exact reference level chosen is not important as long as the user is consistent). The factor $f_{sol}$ is calculated on an hourly basis from the Jungfraujoch neutron monitor and reported on the COsmic ray Soil Moisture Observing System (COSMOS) web portal [9].

The third factor, $f_{hum}$, adjusts the counting rate for changes in the absolute humidity of the atmosphere ($H$). As absolute humidity rises the counting rate tends to drop. According to Rosolem et al. [10], the neutron rate can be corrected with the formula (Table 1.1, column 9)

$$f_{hum} = 1 + 0.0054 \cdot H(t) \tag{1.11}$$

where $H(t)$ is in units of g m$^{-3}$. The absolute humidity of a well mixed atmosphere can be calculated from a local measurement of air temperature ($T$) and relative humidity ($U$) by first calculating the saturation vapour pressure (Table 1.1, column 7)

$$e_w = 6.112 \exp\left( \frac{17.62\,T}{243.12 + T} \right) \tag{1.12}$$

where $e_w$ is in hPa and $T$ is in °C [11], and then calculating absolute humidity (Table 1.1, column 8)

$$H = \frac{U}{100}\left( \frac{e_w k}{T + 273.16} \right) \tag{1.13}$$

where $U$ is expressed as a percentage and $k$ is a constant equal to 216.68 g k J$^{-1}$.

Equation 1.8 also includes the term '$\cdot \ldots \cdot f_i$' in order to emphasize that additional time varying correction factors can be added in the future, as dictated by the outcome of research results. Until such factors are discovered, this term can be assumed to be zero.

The aim of calibration is, in essence, to find the value of $N_0$. An advantage of equation 1.7 is that it is easy to invert, such that

$$N_0 = \frac{N}{\left( F(t) \dfrac{a_0}{(\theta_T / \rho_b) + a_2} \right)^{-1} + a_1} \tag{1.14}$$

It is apparent that the value of $N_0$ is strictly defined for given reference values of $P_0$ and $M_0$, and for the value $H(t)$=0. The choices for $P_0$ and $M_0$ are largely arbitrary—but it is important to remain consistent in using the same reference values for a given site. In the case where the reference conditions are assumed to be the same as the conditions at the time of the calibration, then by definition $F(t)$ = 1 in equation 1.8.

The calibration equation and correction factors continue to be refined and improved. One promising advance is the use of a universal calibration function [12] to overcome the necessity of local calibration. This is important when independent field sampling is prohibitively difficult, and for roving measurements with a mobile CRNS [5, 13] where many types of terrain may be covered in a single campaign. However, soil bulk density, lattice water and aboveground biomass may still need to be measured or derived from maps in order to apply the universal calibration [14]. In principle, explicitly accounting for these variables provides a better calibration, although empirical results [15] have thus far been inconclusive in regard to the significance individual corrections as formulated by Franz et al. [12]. Refer to Baatz et al. [16] who review the advantages and disadvantages of various calibration functions, and to Coopersmith et al. [17] who provide preliminary work on correcting for biomass changes. With the continued adoption of this method around the globe, the scientific community will continue to improve and refine the method of best practice.

An Excel spreadsheet (Table 1.1, Page 15) is provided that demonstrates how to implement the foregoing calibration equations and corrections (raw and processed data). Field and laboratory procedures for obtaining the requisite calibration data are discussed in the Field calibration Section of this publication.

TABLE 1.1. LAYOUT OF THE DATA PROCESSING SPREADSHEET

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Raw Data | | | | | Correction Factors | | | | | | Corrected Counts | Final Data | | | | | |
| | | | | | | Water Vapor Correction | | | | | | | 1-h average | | 12-h average | | |
| UTC | Moderated Counting Rate | Air Pressure | Air Temperature | Relative Humidity | Barometric Factor | Saturated vapor pressure | Absolute humidity | Water Vapor Factor | Solar Factor | Total Factor | Corrected Moderated Counting Rate | Local Time | Soil Water Content | +/- | Local Time | Soil Water Content | +/- |
| | $N$ | $P$ | $T$ | $U$ | $f_{bar}$ | $e_w$ | $H$ | $f_{hum}$ | $f_{sol}$ | $F$ | $F \cdot N$ | | $\theta_p$ | $\sigma_{\theta p}$ | | $\theta_p$ | $\sigma_{\theta p}$ |
| yyyy-mm-dd h:m | Counts $h^{-1}$ | hPa or mb | °C | % | - | hPa | g $m^{-3}$ | - | - | - | Counts $hr^{-1}$ | yyyy-mm-dd h:m | $m^3$ $m^{-3}$ | $m^3$ $m^{-3}$ | yyyy-mm-dd h:m | $m^3$ $m^{-3}$ | $m^3$ $m^{-3}$ |
| 2013-12-11 11:00 | 794 | 1002.4 | 4.1 | 87.3 | 1.02 | 8.2 | 5.59 | 1.03 | 1.02 | 1.07 | 850 | 2013-12-11 13:00 | 0.39 | 0.041 | | | |
| 2013-12-11 12:00 | 787 | 1002.2 | 4.2 | 87.8 | 1.02 | 8.2 | 5.65 | 1.03 | 1.02 | 1.07 | 842 | 2013-12-11 14:00 | 0.40 | 0.043 | | | |
| 2013-12-11 13:00 | 843 | 1001.6 | 4.2 | 88.8 | 1.01 | 8.2 | 5.70 | 1.03 | 1.02 | 1.06 | 898 | 2013-12-11 15:00 | 0.30 | 0.031 | | | |
| 2013-12-11 14:00 | 751 | 1001.4 | 4.1 | 88.9 | 1.01 | 8.2 | 5.68 | 1.03 | 1.02 | 1.06 | 798 | 2013-12-11 16:00 | 0.51 | 0.058 | | | |
| 2013-12-11 15:00 | 744 | 1001.4 | 3.9 | 89.5 | 1.01 | 8.1 | 5.67 | 1.03 | 1.03 | 1.07 | 795 | 2013-12-11 17:00 | 0.52 | 0.059 | | | |
| 2013-12-11 16:00 | 744 | 1001.6 | 3.9 | 91.5 | 1.01 | 8.1 | 5.77 | 1.03 | 1.03 | 1.07 | 797 | 2013-12-11 18:00 | 0.52 | 0.059 | | | |
| 2013-12-11 17:00 | 780 | 1001.2 | 3.7 | 93.3 | 1.01 | 7.9 | 5.80 | 1.03 | 1.03 | 1.07 | 833 | 2013-12-11 19:00 | 0.42 | 0.045 | | | |
| 2013-12-11 18:00 | 785 | 1001.4 | 3.4 | 95.3 | 1.01 | 7.8 | 5.84 | 1.03 | 1.03 | 1.07 | 840 | 2013-12-11 20:00 | 0.41 | 0.043 | | | |
| 2013-12-11 19:00 | 806 | 1001.6 | 3.2 | 97.0 | 1.01 | 7.7 | 5.83 | 1.03 | 1.03 | 1.07 | 863 | 2013-12-11 21:00 | 0.36 | 0.037 | | | |
| 2013-12-11 20:00 | 804 | 1001.6 | 3.2 | 96.2 | 1.01 | 7.7 | 5.79 | 1.03 | 1.03 | 1.07 | 861 | 2013-12-11 22:00 | 0.36 | 0.038 | | | |
| 2013-12-11 21:00 | 774 | 1001.5 | 3.2 | 96.1 | 1.01 | 7.7 | 5.78 | 1.03 | 1.02 | 1.06 | 820 | 2013-12-11 23:00 | 0.45 | 0.050 | | | |
| 2013-12-11 22:00 | 749 | 1001.6 | 3.2 | 92.6 | 1.01 | 7.7 | 5.58 | 1.03 | 1.02 | 1.06 | 793 | 2013-12-12 0:00 | 0.53 | 0.060 | 2013-12-11 19:00 | 0.42 | 0.013 |
| 2013-12-11 23:00 | 810 | 1001.4 | 3.2 | 92.9 | 1.01 | 7.7 | 5.58 | 1.03 | 1.02 | 1.06 | 856 | 2013-12-12 1:00 | 0.37 | 0.039 | 2013-12-11 20:00 | 0.42 | 0.013 |
| 2013-12-12 0:00 | 823 | 1001.1 | 2.9 | 94.1 | 1.01 | 7.5 | 5.56 | 1.03 | 1.02 | 1.05 | 868 | 2013-12-12 2:00 | 0.35 | 0.036 | 2013-12-11 21:00 | 0.42 | 0.013 |
| 2013-12-12 1:00 | 823 | 1000.8 | 2.7 | 95.0 | 1.01 | 7.4 | 5.53 | 1.03 | 1.02 | 1.05 | 866 | 2013-12-12 3:00 | 0.36 | 0.037 | 2013-12-11 22:00 | 0.42 | 0.013 |
| 2013-12-12 2:00 | 795 | 1000.5 | 2.5 | 96.3 | 1.00 | 7.3 | 5.52 | 1.03 | 1.02 | 1.05 | 834 | 2013-12-12 4:00 | 0.42 | 0.045 | 2013-12-11 23:00 | 0.42 | 0.013 |
| 2013-12-12 3:00 | 828 | 1000.3 | 2.3 | 96.9 | 1.00 | 7.2 | 5.49 | 1.03 | 1.01 | 1.04 | 864 | 2013-12-12 5:00 | 0.36 | 0.037 | 2013-12-12 00:00 | 0.40 | 0.012 |
| 2013-12-12 4:00 | 848 | 1000.1 | 2.1 | 97.9 | 1.00 | 7.1 | 5.49 | 1.03 | 1.01 | 1.04 | 884 | 2013-12-12 6:00 | 0.33 | 0.033 | 2013-12-12 01:00 | 0.39 | 0.012 |
| 2013-12-12 5:00 | 767 | 1000.0 | 1.9 | 98.4 | 1.00 | 7.0 | 5.42 | 1.03 | 1.01 | 1.04 | 798 | 2013-12-12 7:00 | 0.51 | 0.058 | 2013-12-12 02:00 | 0.39 | 0.012 |
| 2013-12-12 6:00 | 808 | 1000.0 | 1.5 | 98.6 | 1.00 | 6.8 | 5.31 | 1.03 | 1.01 | 1.04 | 840 | 2013-12-12 8:00 | 0.41 | 0.043 | 2013-12-12 03:00 | 0.39 | 0.012 |
| 2013-12-12 7:00 | 801 | 999.8 | 1.2 | 98.6 | 1.00 | 6.7 | 5.20 | 1.03 | 1.01 | 1.04 | 831 | 2013-12-12 9:00 | 0.43 | 0.046 | 2013-12-12 04:00 | 0.40 | 0.012 |
| 2013-12-12 8:00 | 814 | 999.6 | 1.1 | 98.8 | 1.00 | 6.6 | 5.15 | 1.03 | 1.01 | 1.04 | 843 | 2013-12-12 10:00 | 0.40 | 0.042 | 2013-12-12 05:00 | 0.40 | 0.012 |
| 2013-12-12 9:00 | 838 | 999.6 | 1.0 | 98.8 | 1.00 | 6.5 | 5.11 | 1.03 | 1.01 | 1.03 | 865 | 2013-12-12 11:00 | 0.36 | 0.037 | 2013-12-12 06:00 | 0.40 | 0.012 |

### 1.3.2. Error propagation

The precision of the cosmic ray technique is mainly a function of the counting rate, *N*. Because neutron counting follows Poissonion statistics, it can be shown that the error in the counting rate is simply

$$\sigma_N = \sqrt{N} \qquad (1.15)$$

This can be propagated to the soil moisture determination as a straightforward application of the error propagation formula [18], i.e.

$$\sigma_\theta = \sigma_N \frac{\partial \theta}{\partial N} \qquad (1.16)$$

which yields:

$$\sigma_\theta = \frac{a_1 N_0 \sqrt{N}}{\left(N - a_2 N_0\right)^2} \qquad (1.17)$$

This equation of course neglects any systematic errors in the determination of total soil water components or errors in correction factors. However, the largest source of uncertainty, when counts are integrated over a timescale of less than a few hours, is usually the counting rate.

In Fig. 1.3 the error is expressed as a function of $\theta_V$ and $N_0$, where $N_0$ is the reference counting rate over some arbitrary time base (which needs to match the time base of *N*). It is apparent that higher $N_0$ results in lower error at any given water content. For a given field site, the dry counting rate $N_0$ depends on many variables including the effective size of the detectors, the integration time (time base) and the geographic location of the site. Counting rates increase with elevation and to a lesser extent with latitude, resulting in better precision. A rule of thumb is that the counting rate doubles for every 800 m of elevation. Longer integration times and/or bigger detectors are often required to compensate for low elevation and/or low latitude. Better precision is also achieved at lower water contents, due to higher sensitivity inherent in the shape of the calibration curve.

Importantly, $N_0$ can also be increased (and counting uncertainty reduced) by increasing the integration time — a variable that is always under the control of the user. In many circumstances, such as with the sample data set that accompanies this publication, 12 hour averages are appropriate. Reporting of 12 hour (Table 1.1, column 16 and 17) data is a standard first established for the COSMOS project [9], a project which was largely focused on supporting land surface models. In general, a 12 hour averaging period is recommended here (Table 1.1, column 17), although shorter averages may be possible given the several variables already discussed (Table 1.1, column 14). The error term showed to be much higher in one hour compared to 12 hours average (Table 1.1, column 15 and 18), this would recommend using the 12 hour average.

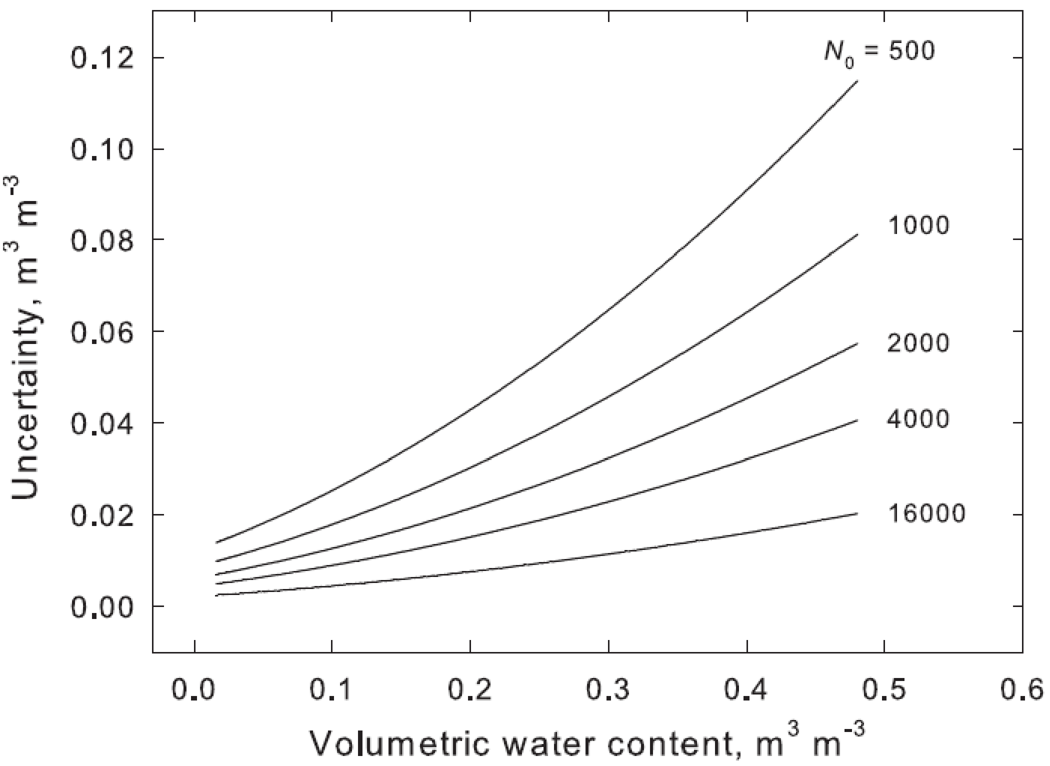


*Fig. 1.3. Uncertainty in soil volumetric water content as a function of water content itself, and for different values of $N_0$ (theoretical dry counting rate).*

## 1.4. SUMMARY

The cosmic ray method has numerous applications to soil moisture monitoring. The basis of the technique is that fast neutrons are generated by cosmic rays and then moderated by collisions with hydrogen. The method provides an average moisture value over a uniquely large lateral radius of approximately 260 m at sea level, and a sample depth integrated over the top several decimetres of soil. Several corrections are required to the raw neutron counting rate, including barometric pressure, a solar activity and absolute humidity corrections, all of which are time varying. A calibration function is then applied to the corrected counting rate, which yields give the total water content. Another form of correction, sometimes necessary, is to subtract certain components of the land surface environment, which are sources of hydrogen in addition to soil moisture. These components are usually constant in time or nearly so. A major source of uncertainty is in the neutron counting rate; this uncertainty easily quantified based on Poissonian counting statistics and then propagated to the soil moisture determination.

## REFERENCES


[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Field Estimation of Soil Water Content, Training Course Series No. 30, IAEA, Vienna (2008).

[2] DESILETS, D., ZREDA, M., Footprint diameter for a cosmic ray soil moisture sensor: theory and monte carlo simulations, Water Resources Research **49** (2013) 3566.

[3] DESILETS, D., ZREDA, M., “Cosmic-ray hydrometrology: Measuring soil moisture with cosmic-ray neutrons”, in Encyclopedia of Remote Sensing: Springer Reference, (E. NJOKU, Ed.), Springer-Verlag, Berlin Heidelberg (2014).

[4] GOLDHAGEN, P., CLEM, J. M.,WILSON, J. W., The energy spectrum of cosmic-ray induced neutrons measured on an airplane over a wide range of altitude and latitude, Radiation Protection Dosimetry **110** (2004) 387.

[5] DESILETS, D., ZREDA, M. AND FERRÉ, T.P.A., Nature's neutron sensor: land surface hydrology at an elusive scale with cosmic rays, Water Resources Research **46** (2010).

[6] ZREDA, M., DESILETS, D., FERRE, T. P. A., AND SCOTT, R. L., Measuring soil moisture content non-invasively at intermediate spatial scale using cosmic-ray neutrons, Geophysical Research Letters **35** (2008).

[7] KÖHLI, M., SCHRÖN, M., ZREDA, M., SCHMIDT U., DIETRICH P., AND ZACHARIAS S., Footprint characteristics revised for field scale soil moisture monitoring with cosmic-ray neutrons, Water Resources Research **51** (2015) 5772.

[8] DESILETS, D., ZREDA, M., AND PRABU, T., Extended scaling factors for in situ cosmogenic nuclides: new measurements at low latitude, Earth and Planetary Science Letters **246** (2006) 265.

[9] ZREDA, M., SHUTTLEWORTH, W. J., ZENG, X., ZWECK, C., DESILETS, D., FRANZ, T., AND ROSOLEM, R., COSMOS: the COsmic-ray Soil Moisture Observing System, Hydrology and Earth System Sciences **16** (2012) 4079.

[10] ROSOLEM, R., SHUTTLEWORTH, W. J., ZREDA, M., FRANZ, T. E., ZENG, X., AND KURC, S. A., The effect of atmospheric water vapour on neutron count in the Cosmic-ray Soil Moisture Observing System, Journal of Hydrometeorology **14** (2013) 1659.

[11] WMO GUIDE, Guide to Meteorological Instruments and Methods of Observation, Appendix 4B, World Meteorological Organization, WMO-No. 8 (CIMO Guide) Geneva (2008).

[12] FRANZ, T. E., ZREDA, M., ROSOLEM, R., AND FERRE, T. P. A., A universal calibration function for determination of soil moisture with cosmic-ray neutrons, Hydrology and Earth System Sciences **17** (2013) 453.

[13] CHRISMAN, B., ZREDA, M, Quantifying mesoscale soil moisture with the cosmic-ray rover, Hydrology and Earth System Sciences **17** (2013) 5097.

[14] FRANZ, T. E., WANG, T., AVERY, W., FINKENBINER, C., AND BROCCA, L., Combined analysis of soil moisture measurements from roving and fixed cosmic ray neutron sensors for multiscale real-time monitoring, Geophysical Research Letters **42** (2015).

[15] MCJANNET, D., FRANZ, T.E., HAWDON, A, BOADLE D., BAKER, B., ALMEIDA A., SILBERSTEIN R., LAMBERT, T. AND DESILETS, D., Field testing of the universal calibration function for determination of soil moisture with cosmic-ray neutrons, Water Resources Research **50** (2014) 5235.

[16] BAATZ, R., BOGENA, H.R., FRANSSEN, H.J.H., HUISMAN, J.A., QU, H., MONTZKA, C., AND VEREECKEN, H., Calibration of a catchment scale cosmic-ray sensor network: a comparison of three parameterization methods, Journal of Hydrology **516** (2014) 231.

[17] COOPERSMITH, E. J., COSH, M.H., AND DAUGHTRY, C.S.T., Field-scale moisture estimates using COSMOS sensors: a validation study with temporary networks and leaf-area-indices, Journal of Hydrology **519** (2014) 637.

[18] KU, H. H., Notes on the use of propagation of error formulas, Journal of Research of the National Bureau of Standard **70C** (1966) 262.

# CHAPTER 2. DESCRIPTION AND FIELD INSTALLATION OF A COSMIC RAY SOIL MOISTURE SENSOR

T.E. FRANZ
School of Natural Resources,
University of Nebraska Lincoln,
Nebraska USA

D. DESILETS
HydroInnova LLC,
Albuquerque, New Mexico USA

W. AVERY
Soil and Water Management & Crop Nutrition Subprogramme, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, Austria

## 2.1. INTRODUCTION

In this Chapter a general description of a Cosmic Ray Neutron Sensor (CRNS) is given. Additionally, the typical field installation procedure for the CRNS technique is described. Each field site is different, and may require some improvisation by the installer. A properly installed sensor can go many years with little or no maintenance if the installation is carefully done.

## 2.2. EQUIPMENT DESCRIPTION

A CRNS generally consists of one or two metal cylindrical sensors containing either Helium-3 or Boron Trifluoride gas. These sensors are cabled to a data logger and thermalized neutron counter housed in a separate enclosure. A 12 V battery is connected to the system as well as an external solar panel to provide power. The sensors, data logger, and housing box are mounted on a large steel pole anchored to the ground via a cement filled hole.

## 2.3. COMPONENTS

The following list details the necessary components of any CRNS device when deployed in the field:

(a) Soil moisture sensors
(b) Data logger
    i) Outdoor rated enclosure for data logger and battery
    ii) Cellular or satellite modem
    iii) Tube capsule mounting brackets
    iv) Data cables (between sensors and data logger)
        — Internal sensors for
        — Air temperature

— Relative humidity
— Barometric pressure

(c) External sensors (provided on request) for
  i. Air temperature
  ii. Relative humidity
(d) Solar charge controller with low voltage disconnect
(e) Satellite or cellular antenna
(f) TNC-F to TNC-F adapter for attaching antenna to enclosure
(g) Deep cycle battery
(h) Solar panel, brackets and charging cable
(i) Pole§, tripod, or other structure (on which to mount sensor)
(j) U-bolts/hose clamps (for securing sensor and solar panel to pole)
(k) Bag of cement (if using pole)
(l) Water for mixing cement

§Typically Diametre Nominal 50 mm (DN 50) or 2 inch Nominal Pipe Size (NPS 2), Schedule 30 or greater.

### 2.3.1. Setting up the instrument

The following diagrams illustrate the equipment needed to properly install a CRNS device in the field:


*Fig. 2.1. Equipment and materials needed by the user: (A) short step ladder, (B) pipe wrench, (C) tool bag (see following figure for contents), (D) water, (E) quick set cement, (F) shovel, (G) pole (the one shown here comes in two pieces which can be mated), and (H) digging bar (i.e. for hard/rocky soils).*

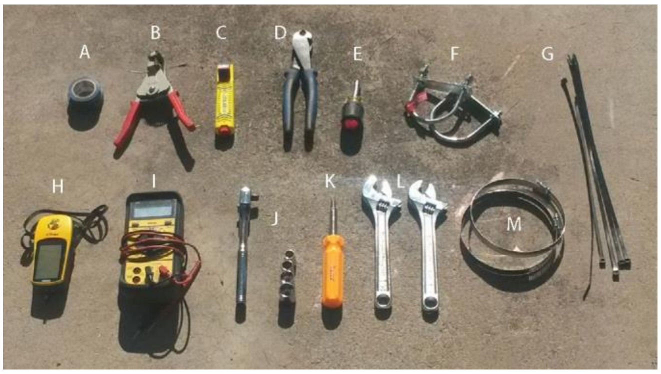


*Fig. 2.2. Contents of the installer's tool bag: (A) electrical tape, (B and C) wire strippers for small and large diameter cables, (D) wire cutters, (E) hex driver, (F) U-bolts, (G) cable ties, (H) handheld GPS, (I) voltmeter, (J) ratcheting socket driver and sockets, (K) four-in-one driver set, (L) adjustable wrenches and (M) stainless steel hose clamps.*

#### *2.3.1.1. Recommended tools*

The following list details recommended tools for field CRNS installation:

- Spade shovel for digging and backfilling post hole.
- Digging bar for loosening hard or rocky soils.
- Short step ladder for reaching solar panel or top of enclosure.
- Socket Wrench for assembling solar panel brackets. Two wrenches are usually required — one to turn the bolt and one to hold the nut on the other side.
- Adjustable wrench for tightening U-bolts.
- Pipe wrench for assembling two piece threaded pole (optional).
- Four-in-one driver set. Contains Phillips head driver for adjusting screw terminals on charge controller and flat head for tightening hose clamps and charge controller terminals.
- Hex driver for tightening hose clamps.
- Voltmeter for checking battery charge and for troubleshooting power connections.
- Wire cutters for cutting power cable.
- Wire strippers for stripping power leads (Figs 2.1 and 2.2).

#### *2.3.1.2. Example installation procedure*

The following is an example installation procedure for a CRNS device:

1. Unpack all equipment in the laboratory to verify that all cables and parts required are present. Become familiar with the pieces and how they would fit together in the field before heading out.

2. Obtain any additional parts and tools needed for the installation. Typically a trip to a local hardware store is sufficient.

3. Save time in the field by preassembling the solar panel brackets and attaching the panel to the brackets in the laboratory before the day of the field installation. Avoid damage to the panel during transport to the field site. Covering or packing the panel with cardboard will help protect the panel.

4. On the day of the installation, secure the mast to the ground with cement. For a mast that is 3 m long, dig to a depth of 60-90 cm and use a ~20 kg bag of quick setting concrete to stabilize the pole. Let the concrete set for half an hour before mounting instruments on the mast.

5. Mount sensors and data logger box.

   Using U-bolts or hose clamps, mount the data logger box approximately 1.5 m off the ground. The sensors are typically centred at approximately this 1.5 m level. The sensors and data logger box can be mounted higher if necessary to avoid coverage by snow, water or understory vegetation.

6. Secure the solar panel assembly to the pole at a location above the data logger enclosure using U-bolts or sturdy hose clamps. Face the panel to true South (true North in southern hemisphere). To ensure optimal charging in winter the following tilt angle relation can be used:

   Tilt Angle = Latitude + 15°

   where Tilt Angle is measured relative to horizontal.

7. Attach the antenna.

   If possible, attach antenna to top of data logger enclosure. For the *Iridium* satellite antenna, use the provided TNC-F to TNC-F adapter. For an antenna with TNC-M connection, simply screw directly onto the TNC-M feed through located at the top of the enclosure. Alternatively, a coaxial cable can be used to locate the antenna elsewhere if desired.

   Note that the solar panel will not block the *Iridium* transmissions.

8. Mount external T/RH sensor with provided U-bolt to a location above the top of the instrument box. A user provided cross arm can be used.

9. Insert battery into the bottom of the data logger box and then wire the battery to the appropriately labelled terminals on the solar charge controller. To avoid a short circuit, wire one pole of the battery at a time, starting with positive terminal. Make sure not to cross the wires once they are connected to the battery.

10. Wire the solar panel to the appropriately labelled terminals on the solar charge controller. Use wire strippers to strip the power leads from the solar power cable.

Make sure the data logger power cable is wired to the Load terminals on the charge controller, and connect power cable to the data logger

11. Flip toggle switch on data logger to On. Secure any loose or excess cable excess using outdoor rated cable ties.

12. Before leaving, be sure to add a bag of desiccant to the enclosure.

13. Secure the enclosure door using padlock.

*2.3.1.3. Power*

*(a) Solar power*

A solar charge controller is included with most sensors. This device regulates power from photovoltaic cells, applying a charging voltage of about 14.1 VDC from a nominal 12 VDC solar panel. Use of a charge controller is critical to prevent overcharging the battery. It will also prevent deep discharge of the battery. In the case of an undercharging battery (e.g. insufficient sunshine) the controller will automatically disconnect power to the sensor once the battery has drained to less than 11.5 VDC. Power will automatically be returned to the sensor once the battery is recharged past a threshold of 12.6 VDC.

*(b) AC grid power*

For running the sensor off AC grid power, the manufacturer recommends using an AC-DC converter at the AC outlet and then running a 12 VDC power cable to the sensor. Because of the low current requirements for the sensor, the power cable can be quite long (hundreds of meters) with minimal drop in voltage. The flying leads from the 12 VDC power cable are terminated with spade connectors, which are then be connected to the solar inputs on the charge controller. Running the already regulated power through the charge controller will enable use of a battery for backup power and allows use of the low-voltage disconnect feature, which will ensure that the battery is not irreversibly discharged during a long AC power outage.

*2.3.1.4. Cabling*

*(a) Power cables*

All sensors require an external power source if the sensors are to be operated for more than a few days. The cable typically consists of at least two 0.75 $mm^2$ (20 AWG) conductors with an outdoor rated shield (note that minimum cable sizes will depend on the solar panel wattage, among other factors).

*(b) Data cables for tube capsules*

External cabling is also often needed between tube capsules and data logger. The cables provided by the manufacturer are an outdoor rated (PVC jacketed) CAT5 cable. The cable is mated to the tube capsule using a special water tight cable gland. At the data logger end, the cable is terminated with a standard RJ45 plug, which is passed through cable glands on data logger entry.

For an arctic environment, where cables will potentially be handled at temperatures of -20° C or lower, special CAT5 cabling may be required. This cabling contains a dielectric gel that will impede the conductors from shorting if their plastic insulation become compromised. In addition, armoured CAT5 cable may be needed in some situations, particularly where cable is run along the ground surface and is accessible to rodents and other animals. In these situations the user can contact the manufacturer of the sensor for more information on obtaining suitable cables.

*(c) Splitters and junction boxes*

CRNS devices are best designed to accept inputs from two tube capsules, but sometimes additional tube capsules are desired. These additional channels can be accommodated by using an RJ45 splitter module which can be added to a data logger enclosure. Many splitters can be combined to create a standalone junction box which can then be connected via a single cable to a data logger enclosure. This is possible because channels can be uniquely addressed using SDI12 protocols. Before using a junction box to add sensors, the user will ensure that each tube is uniquely addressed.

*(d) Cable length*

Because the separation between the data logger and tube capsules is typically small, the data cables are typically short. But it is possible to separate tube capsules from the data logger by up to 500 m. Several capsules can be connected to a junction box, and then the junction box to a remote data logger via a single cable. This is possible so long as the total cable length from the data logger to any individual capsule does not exceed 500 m.

### 2.3.2. Data format

Raw data should typically be reported in the following format (Table 2.1):

TABLE 2.1. TYPICAL DATA OUTPUT FROM A CRNS

| Columns: 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| YY-MM-DD HH:MM, UTC | Mod, cts $h^{-1}$ | Bare, cts $h^{-1}$ | Pressure, hPa | Temperature, °C | RH, % | Batt, V |
| 2010-06-08 00:02 | 828 | 466 | 923.0 | 28 | 37 | 12.5 |
| 2010-06-08 01:02 | 869 | 407 | 923.3 | 27 | 37 | 12.4 |
| 2010-06-08 02:02 | 810 | 440 | 923.1 | 28 | 38 | 12.4 |
| 2010-06-08 02:38 | 866 | 425 | 932.6 | 25 | 46 | 12.4 |

**Note:** Column numbers represent:
1: Date and time at end of record period in Universal Time;
2: Counting rate from the moderated neutron channel in counts per hour;
3: Counting rate from the bare neutron channel (if present) in counts per hour;
4: Barometric pressure;
5: Air temperature;
6: Relative humidity;
7: Battery voltage.

Additional sensors, including other neutron counting channels, may also be present depending on the configuration of the sensor.

Other data recorded by the logger, but not telemetered unless needed, include pulse height histograms from the detector tubes. These histograms provide diagnostic information that can help troubleshoot problems with the sensor. This information is generally used only by the manufacturer.

#### *2.3.2.1. Data levels*

Data from the CRNS are classified according to their level of processing. Based on practices established by the US National Science Foundation's Cosmic Ray Soil Moisture Observing System (COSMOS) project [1], suggesting the following classifications:

Level 1: Reports raw counts from moderated and bare channels as well as raw data from ancillary sensors. Also reports sensor diagnostics for quality control purposes. Neutrons are counted over a time period (usually one hour) and count totals are reported at the end of each period.

Level 2: Takes raw, Level 1 data and converts them to a format suitable for soil moisture computation. The data are quality controlled, typically such that spuriously high or low counting rates are flagged and excluded from Level 2. Corrections for barometric pressure, atmospheric relative humidity and vegetation, if applicable, are included here.

Level 3: Takes quality controlled, corrected Level 2 data and converts them directly to an integrated soil moisture measurement. These data represent average values over the footprint and sample depth of the sensor, and over some time interval which is greater than or equal to that of the Level 1 data.

Level 4: Value added data products derived from lower level data. This includes variables such as soil water depletion, root zone moisture content or soil depth profiles. Level 4 data may rely on model simulations and/or assimilation of ancillary data.

## 2.4. SUMMARY

In this Chapter description of the equipment, installation tools and other practical issues related to installing a CRNS in the field was provided. A step-by-step instruction on installing a sensor was also provided. The general potential format of raw data is discussed, as are data levels related to various degrees of processing of the raw data.

## REFERENCES

[1] ZREDA, M., SHUTTLEWORTH, W. J., ZENG, X., ZWECK, C., DESILETS, D., FRANZ, T., AND ROSOLEM, R., COSMOS: the COsmic-ray Soil Moisture Observing System, Hydrology and Earth System Sciences **16** (2012) 4079.

# CHAPTER 3. FIELD CALIBRATION AND VALIDATION OF A COSMIC RAY SOIL MOISTURE SENSOR

A. WAHBI, G. WELTIN, L. K. HENG, G. DERCON, AND W. AVERY
Soil and Water Management & Crop Nutrition Subprogramme, Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, International Atomic Energy Agency, Austria

M. VREUGHENHIL, AND M. OISMUELLER
Centre for Water Resource Systems,
Vienna University of Technology,
Vienna, Austria

P. STRAUSS
Federal Agency for Water Management,
Institute for Land & Water Management Research,
Petzenkirchen, Austria

T.E. FRANZ
School of Natural Resources,
University of Nebraska Lincoln,
Nebraska USA

D. DESILETS
HydroInnova LLC,
Albuquerque, New Mexico USA

## 3.1. INTRODUCTION

One challenge with a technique that operates at a uniquely large scale is the lack of complementary methods available for calibrating the measurements or for verifying the accuracy of data over time. In the case of a cosmic ray soil neutron sensor (CRNS), out of necessity one usually relies on aggregating many point samples within the footprint of the sensor to get a complimentary scale. In this section discussion, on how point sampling techniques have been used to provide either direct but intermittent data or continuous but indirect data for calibration and validation, was provided. Also discuss procedures for collecting additional site data, usually done on the day of installation, which are needed to accurately calibrate the sensor using the equations in Chapter 1.

## 3.2. CALIBRATION

The key information required to calibrate the sensor, in ascending order of importance, are:

(1) Soil water content (typically volumetric water content)
(2) Soil bulk density
(3) Clay structural (lattice) water
(4) Soil organic carbon

(5) Standing wet and dry biomass

These properties are estimated within the footprint of the sensor. Note that in soils with a sandy texture, (3) and (4) can be neglected, (2) can usually be determined with a small number of samples, and (5) vegetation changes are often small over the season in which case they can be ignored.

### 3.2.1. Volumetric water content and soil bulk density

The spatial distribution of pore (gravimetric) water can be highly variable, requiring many samples in order to get an accurate spatial average. The gravimetric campaign consisted of averaging individual samples, by collecting samples at 3 depths (0–5, 5–10 and 15–20 cm; total of 61 samples) for 16 locations (Figs 3.1, 3.2 and 3.3) [1]. As seen from Fig. 3.1, the footprint consists of different crops; this could produce some errors in the calibration depending on the date of sampling. Recent publications suggested more than one gravimetric sampling to include the full range of soil moisture and cropping pattern [2]. Therefore, additional 3 sampling campaigns were performed (at different timing) at 18 locations and 3 depths (0–10, 10–20 and 20–30 cm) (54 total) which will provide additional information of the mean volumetric water content with low standard error ($\sigma < 0.01$ m$^3$ m$^{-3}$). The sample locations are every 60 degrees (0, 60, 120, 180, 240, and 300) and radii of 25, 75, and 200 m (Fig. 3.4). This pattern was chosen such that each sample location (and representative area) is given equal weight in the CRNS sensitivity (sensitivity dies off exponentially from sensor). Note that the sample locations don't need to be exact — within a several meters of the targeted location is sufficient, so long as sample locations are not biased by human judgment.

As a practical matter, retaining undisturbed samples can be difficult with any coring apparatus. However, it is recommended that at least one undisturbed sample is taken so that the volume of each soil core section is accurately known. Then the soil bulk density and volumetric water content can be estimated by gravimetric methods. The standard gravimetric method is to obtain the wet soil weight and dry soil weight following oven drying at 105°C for 24 to 48 hours (until weight is constant).

*Note*: while in the field, always tape around the seam of the filled soil can to prevent unwanted drying or soil losses of the samples.

### 3.2.2. Structural water and soil organic carbon

These are determined on a subset of the samples collected for water content and bulk density. Structural water is water contained in the mineral lattice of clay particles, and hence is higher in clay-rich soils (data base is available relating soil texture to lattice water which enable the calculation of lattice water from measured soil texture). Soil organic carbon water equivalence is the amount of water contained in the organic carbon compounds assuming the compounds are cellulose ($C_6H_{10}O_5$). These analyses can be done by commercial laboratories (e.g. Actlabs Inc. of Ontario, Canada). For expedience, it is acceptable to create one composite sample for analysis by the commercial laboratory. Following oven drying and weighing of the gravimetric water samples, this composite sample can be created by taking approximately 1 g from each sample can.

### 3.2.3. Vegetation in cropping areas

One can either set out a 50×50 cm sampling square or calculate the number of plants per unit area. A common practice is to sample 5–7 locations around the CRNS footprint. For biomass sampling, it is best to cut the vegetation near the ground surface and then place it in a brown paper bag. Then weigh the wet sample, and place the sample in an oven at 70°C for 5 days to determine the dry weight of the sample. With this information, calculation of the mass of water and the mass of dry plant can be determined. The water equivalent of dry plant (cellulose) to water is the dry weight multiplied by 0.5556. This will be further exploring in future research.

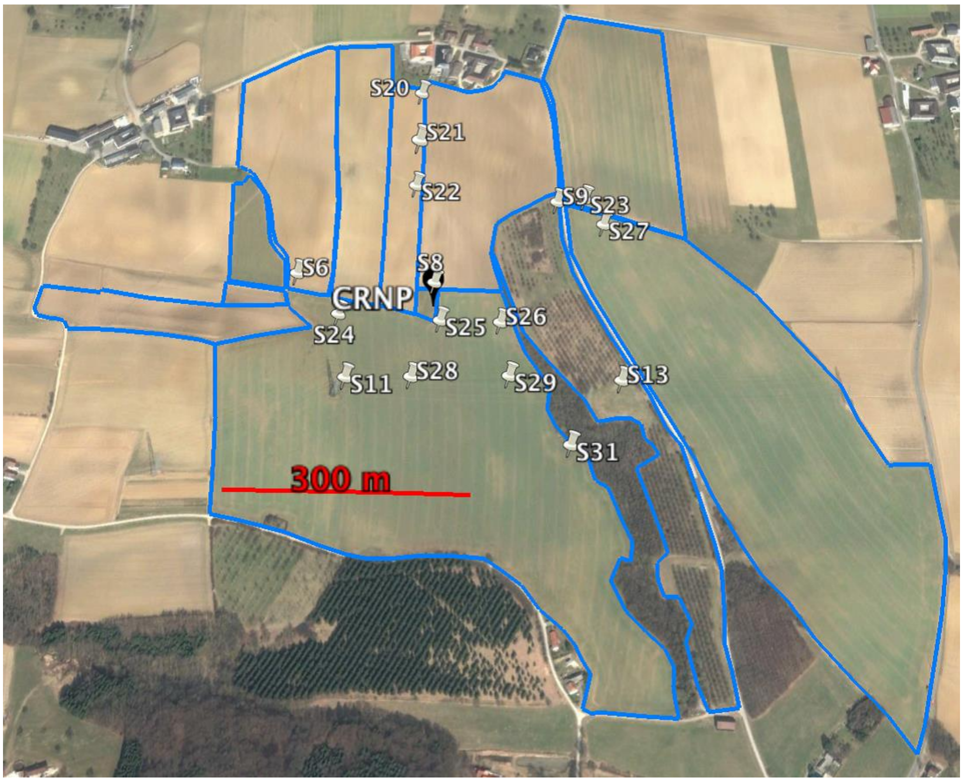


*Fig.3.1. Location of 16 sites for soil moisture profiles (sensor measurement depths at 0-5 cm, 5-10 cm, 15-20 cm, and 45-50 cm) within the radial CRNS footprint[1].*

*Fig. 3.2. Volumetric sampling. The slide hammer is used to insert the core, dug out to prevent shearing of pieces, and split apart for placement of samples in soil cans.*

*Fig. 3.3. The soil cans are filled and taped for later weighing in the laboratory.*

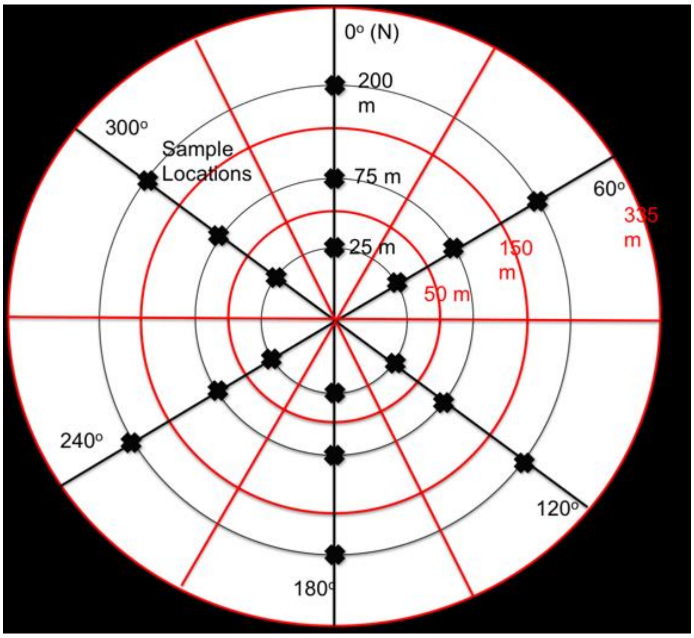


*Fig. 3.4. Field sampling diagram. Black x marks denote sampling locations in the CRNS footprint. Each location is representative of an annular sector defined by red circles and radial lines. The area of each sector is inversely proportional to the sensitivity of the CRNS as a function of distance.*

## 3.3. VALIDATION

Because no other instrument operates at a comparable scale, field validation campaigns are fraught with difficulty. Validation is probably best accomplished by comparing the sensor to an aggregate of a large number of point samples. The preferred method is to compare the sensor against the most reliable truth — direct measurements of water content determined from oven dried soil cores. Field campaigns can be done at different times of the year, with each point in time representing different average water contents. While this procedure is reliable and accurate, it has drawbacks of being labour intensive and only capable of providing intermittent data. Several investigators have therefore relied on dense networks of buried electromagnetic sensors (e.g. time domain frequency or reflectometry sensors, time domain transmissivity sensors, impedance sensors) for indirect comparison of soil water content, which have the advantage of providing continuous data for analysing soil moisture dynamics. The drawback is that these independent measurements are indirect, and are themselves also subject to be inaccuracies and unbiased which may limit their usefulness. Locations of some of the major published validation campaigns are shown in Fig. 3.5.

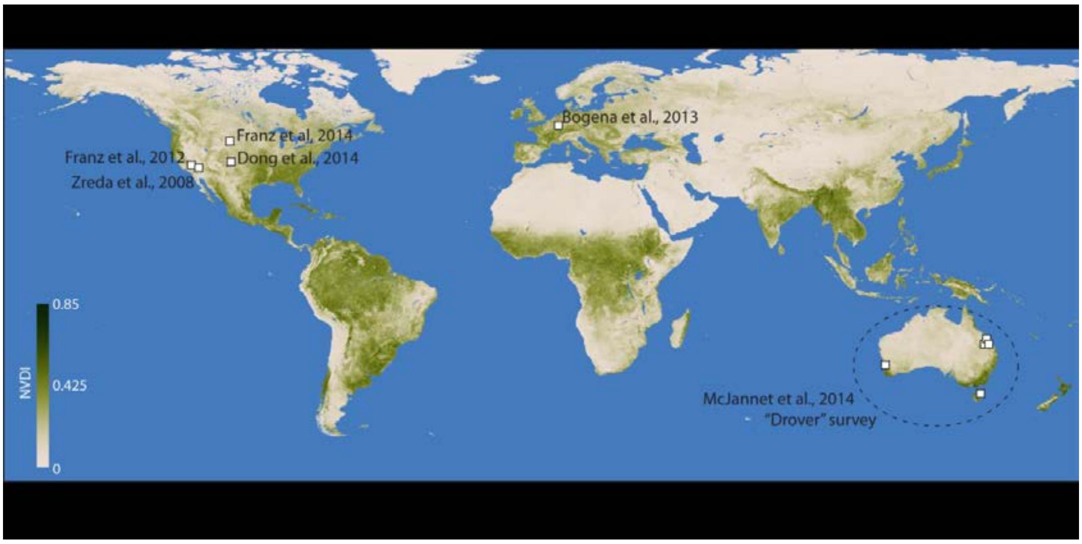


*Fig. 3.5. Validation sites across the world. Climate gradients are indicated by the shading, which is the Normalized Vegetation Difference Index for week of 3-9 November, 2014 inferred from satellite data (http://www.nnvl.noaa.gov/view/).*

*Fig. 3.6. Network of TDT sensors at different depths.*

A network of time domain transmissivity (TDT) sensors (SPADE, Juelich, Germany) were installed. The TDT sensors record half hourly soil water content at a point and were installed at 16 sites distributed around the study area (Fig. 3.1 illustrates the 16 sites within the CRNS measurement area) [1].

"At each site 4 TDT sensors were installed horizontally at 4 depths (representing soil layers of ~0–5 cm, 5–10 cm, 15–20 cm, and 45–50 cm; Fig. 3.6). Depending on routine agricultural operations and location of the stations, the TDT sensors are removed at various times throughout the year. The network of TDT sensors was used to independently compare against the CRNS observations of landscape soil water content" [1]. It was noted that given the limited distribution of sensors and spatially varying soil water content [3], establishing true landscape average soil water content is challenging and a comparison against the CRNS can only be framed within the expected uncertainty of the mean given the inherent limitations of spatial representativeness of averaging a few point sensors in an area.

The key points drawn from the TDT network are: 1) relative changes of TDT response to rainfall across sites are consistent, 2) estimates of the landscape soil water content are uncertain (~0.02 $m^3$ $m^{-3}$ standard error of the mean and 0.07 $m^3$ $m^{-3}$ standard deviation for range of soil water content and all soil depths), and 3) absolute values of soil water content for a single site are not representative of the landscape soil water content for all depths. The wide spatial variability of soil water content is reported elsewhere [3] using higher density time domain reflectometry (TDR) surveys.

Figure 3.7 illustrates that the CRNS compares well against the independent TDT network observations given the standard error of the mean at +/- 0.02 $m^3$ $m^{-3}$ for the TDT landscape average. Most importantly the CRNS and shallow TDT sensors all respond to precipitation (Fig. 3.7) and decrease at similar rates. Figure 3.8 illustrates the comparison of daily data between the landscape TDT and CRNS between 15 December and 1 May 2014. These data were selected so that at least 5 TDT sites were used in creating the landscape average and standard error of the mean. In terms of the absolute soil water content comparison (Fig. 3.8) it showed that the root-mean-square error (RMSE) = 0.0333 $m^3$ $m^{-3}$ is comparable to other studies in various natural ecosystems (mixed montane forest [4], semiarid shrubland [5], deciduous forests in the eastern USA [6] and Germany [7]) and is on the same order of magnitude as the TDT sensors averaged by depth. The bias of 0.08 was likely due in part to differences between the TDT factory calibration and local field conditions. Overall the comparison between the TDT network average and CRNS was within acceptable error of <0.04 $m^3$ $m^{-3}$ used in validating remote sensing products against ground observations [8, 9].

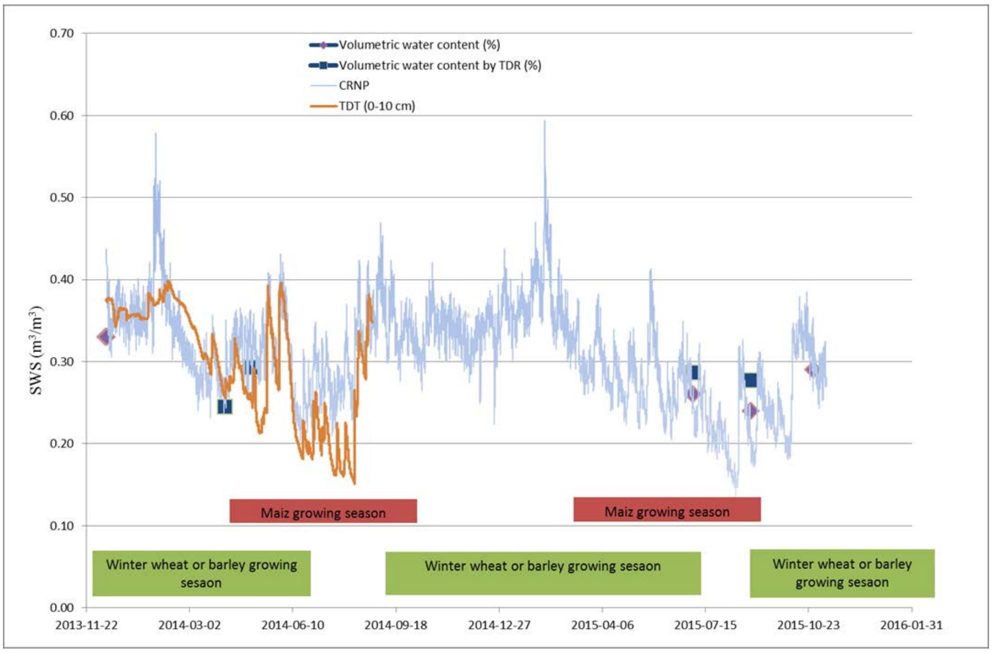


*FIG.3.7. Time series of site average soil water content of TDT values at 0-10 cm depth, soil water content from the CRNS, and independent gravimetric (12 December 2013,and 3 July, 28 August and 28 October 2015) and TDR sampling campaigns (5 and 30 April 2014 and 3 July and 28 August 2015) at Petzenkirchen research station.*

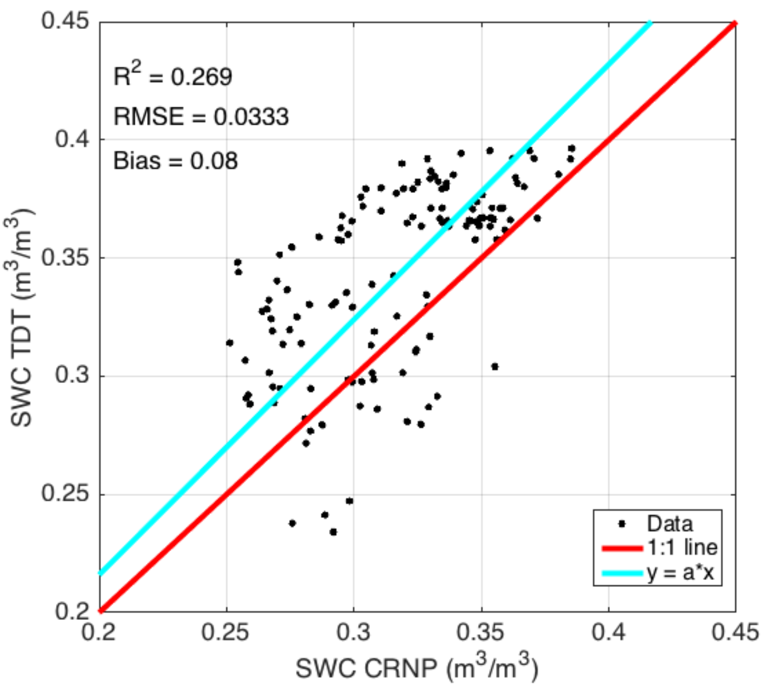


*FIG. 3.8. Comparison of daily soil water content between the CRNS and independent TDT sensors (averaged from 0-20 cm) between 15 December 2013 and 1 May 2014. Note the RMSE is on the same order of magnitude (~0.033 $m^3$ $m^{-3}$) as the standard error of the mean (+/- 0.02 $m^3$ $m^{-3}$) of the TDT sensors for each depth.*

Bogena et al. (2013) tested the limits of the technique through an experiment in the humid Wüstebach forest of Germany [7]. This climate setting contrasts with the semiarid southwestern US, where much of the work cited above took place. The Wüstebach site is more challenging than the southwestern US due to the lower elevation, which provides a lower baseline counting rate; wet soils, which mean lower counting rate and intrinsically less sensitivity to soil moisture; and biomass, which is likely a confounding influence on the neutron counting rate. The investigators utilized a distributed network of 150 wireless dielectric sensors (SoilNet) at Wüstebach to provide independent data within the footprint of a CRNS. Bogena et al. found that daily averaged soil water between the SoilNet and CRNS agreed to within a RMSE of about 0.03 $cm^3$ $cm^{-3}$. The authors reported that better accuracy could be achieved by explicitly considering the litter layer with numerical modelling simulations.

As a final commentary on past, as well as prospective validation efforts, let it be emphasized that disagreements between the CRNS and independent methods can have many possible root causes — including problems with the independent method. There is no field observation strategy that can perfectly match the scale of the CRNS. Nonetheless, in the experiments described above, disagreements with the CRNS have mostly been negligible or small enough that an error in the independent technique or in analysis of the data (for example in most studies to date weighting of the sample depth has not been rigorously addressed) could be partly responsible. More importantly, at some locations, particularly where rocks, roots or caliche are abundant, field validation may be impossible. It is worth noting that these locations are exactly where data from the CRNS may be most valuable — i.e. where there is a complete lack of viable alternatives.

## 3.4. SUMMARY

In this Chapter, the procedures for calibrating a CRNS using independent soil measurements were discussed. This calibration process usually involves using a coring apparatus to take tens of volumetric soil samples in a radial pattern around the sensor. A number of subsamples are necessary to measure clay lattice water content and soil organic carbon content, so that these apparent water content components can be accounted for. Standing wet and dry biomass is also often measured in order to improve the accuracy of the soil moisture determination. Several examples were provided on validation work involving repeated campaign style volumetric sampling or indirect but continuous time series from a network of sensors.

## REFERENCES


[1] FRANZ, T. E., WAHBI, A., VREUGHENHIL, M., WELTIN, G., HENG, L., OISMUELLER, M., STRAUSS, P., DERCON, G., DESILETS, D., Using cosmic-ray neutron sensors to monitor landscape scale soil water content in mixed land use agricultural systems, Applied and Environmental Soil Science (2016) 11 pages.

[2] IWEMA, J., ROSOLEM, R., BAATZ, R. WAGENER, T., BOGENA, H. R., Investigating temporal field sampling strategies for site-specific calibration of three soil moisture–neutron intensity parameterisation methods, Hydrology and Earth Systems Sciences **19** (2015) 3203.

[3] BLOSCHL, G., BLASCHKE, A. P., BROER, M., BUCHER, C., CARR, G., CHEN, X., EDER, A., EXNER-KITTRIDGE, M., FARNLEITNER, A., FLORES-OROZCO, A., HAAS, P., HOGAN, P., KAZEMI AMIRI, A., OISMULLER, M., PARAJKA, J., SILASARI, R., STADLER, P., STRAUB, P., VREUGDENHIL, M., WAGNER,W., ZESSNER, M., The Hydrological Open Air Laboratory (HOAL) in Petzenkirchen: a hypotheses driven observatory, Hydrology and Earth Systems Sciences Discussions **12** (2015) 6683.

[4] LING, L.V., FRANZ, T. E., ROBINSON, D. A., JONES, S. B., Measured and modeled soil moisture compared with cosmic-ray neutron sensor estimates in a mixed forest. Vadose Zone Journal **13** (2014).

[5] FRANZ, T. E., ZREDA, M., ROSOLEM, R., AND FERRE, P. A., Field validation of cosmic-ray soil moisture sensor using a distributed sensor network, Vadose Zone Journal **11** (2012).

[6] COOPERSMITH, E. J., COSH, M.H., DAUGHTRY, C.S.T., Field-scale moisture estimates using COSMOS sensors: A validation study with temporary networks and Leaf-Area-Indices, Journal of Hydrology **519** (2014) 637.

[7] BOGENA, H. R., HUISMAN, J. A., BAATZ, R., HENDRICKS FRANSSEN, H.-J., VEREECKEN, H., Accuracy of the cosmic-ray soil water content sensor in humid forest ecosystems: The worst case scenario, Water Resources Research **49** (2013) 5778.

[8] ENTEKHABI, D., NJOKU, E. G., O'NEILL, P. E., KELLOGG, K. H., CROW, W. T., EDELSTEIN, W. N., ENTIN, J. K., GOODMAN, S. D., JACKSON, T. J., JOHNSON, J., KIMBALL, J., PIEPMEIER, J. R., KOSTER, R. D., MARTIN, N., C. MCDONALD, K., MOGHADDAM, M., MORAN, S., REICHLE, R., SHI, J. C., SPENCER, M. W., THURMAN, S. W., TSANG, L., VAN ZYL, J., The soil moisture active passive (SMAP) mission, Proceedings of the Ieee **98** (2010) 704.

[9] KERR, Y. H., WALDTEUFEL, P., WIGNERON, J. P., DELWART, S., CABOT, F., BOUTIN, J., ESCORIHUELA, M. J., FONT, J., REUL, N., GRUHIER, C., JUGLEA, S. E., DRINKWATER, M. R., HAHNE, A., MARTIN-NEIRA, M., MECKLENBURG, S., The SMOS mission: new tool for monitoring key elements of the global water cycle, Proceedings of the Ieee **98** (2010) 666.

## CONTRIBUTORS TO DRAFTING AND REVIEW

| | |
|---|---|
| Avery, W. | International Atomic Energy Agency |
| Dercon, G. | International Atomic Energy Agency |
| Desilets, D. | HydroInnova LLC, United States of America |
| Franz, T. | University of Nebraska, United States of America |
| Heng, L. | International Atomic Energy Agency |
| Oismueller, M. | Vienna University of Technology, Austria |
| Strauss, P. | Federal Agency for Water Management, Austria |
| Vreugdenhil, M. | Vienna University of Technology, Austria |
| Wahbi, A. | International Atomic Energy Agency |
| Weltin, G. | International Atomic Energy Agency |

# ORDERING LOCALLY

In the following countries, IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

**BELGIUM**
***Jean de Lannoy***
Avenue du Roi 202, 1190 Brussels, BELGIUM
Telephone: +32 2 5384 308 • Fax: +32 2 5380 841
Email: jean.de.lannoy@euronet.be • Web site: http://www.jean-de-lannoy.be

**CANADA**
***Renouf Publishing Co. Ltd.***
22-1010 Polytek Street, Ottawa, ON K1J 9J1, CANADA
Telephone: +1 613 745 2665 • Fax: +1 643 745 7660
Email: order@renoufbooks.com • Web site: http://www.renoufbooks.com

***Bernan Associates***
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

**CZECH REPUBLIC**
***Suweco CZ, s.r.o.***
SESTUPNÁ 153/11, 162 00 Prague 6, CZECH REPUBLIC
Telephone: +420 242 459 205 • Fax: +420 284 821 646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

**FRANCE**
***Form-Edit***
5 rue Janssen, PO Box 25, 75921 Paris CEDEX, FRANCE
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: fabien.boucard@formedit.fr • Web site: http://www.formedit.fr

***Lavoisier SAS***
14 rue de Provigny, 94236 Cachan CEDEX, FRANCE
Telephone: +33 1 47 40 67 00 • Fax: +33 1 47 40 67 02
Email: livres@lavoisier.fr • Web site: http://www.lavoisier.fr

***L'Appel du livre***
99 rue de Charonne, 75011 Paris, FRANCE
Telephone: +33 1 43 07 43 43 • Fax: +33 1 43 07 50 80
Email: livres@appeldulivre.fr • Web site: http://www.appeldulivre.fr

**GERMANY**
***Goethe Buchhandlung Teubig GmbH***
Schweitzer Fachinformationen
Willstätterstrasse 15, 40549 Düsseldorf, GERMANY
Telephone: +49 (0) 211 49 874 015 • Fax: +49 (0) 211 49 874 28
Email: kundenbetreuung.goethe@schweitzer-online.de • Web site: http://www.goethebuch.de

**HUNGARY**
***Librotrade Ltd., Book Import***
Pesti ut 237. 1173 Budapest, HUNGARY
Telephone: +36 1 254-0-269 • Fax: +36 1 254-0-274
Email: books@librotrade.hu • Web site: http://www.librotrade.hu

**INDIA**
***Allied Publishers***
1st Floor, Dubash House, 15, J.N. Heredi Marg, Ballard Estate, Mumbai 400001, INDIA
Telephone: +91 22 4212 6930/31/69 • Fax: +91 22 2261 7928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

***Bookwell***
3/79 Nirankari, Delhi 110009, INDIA
Telephone: +91 11 2760 1283/4536
Email: bkwell@nde.vsnl.net.in • Web site: http://www.bookwellindia.com

**ITALY**
***Libreria Scientifica "AEIOU"***
Via Vincenzo Maria Coronelli 6, 20146 Milan, ITALY
Telephone: +39 02 48 95 45 52 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Web site: http://www.libreriaaeiou.eu

**JAPAN**
***Maruzen-Yushodo Co., Ltd.***
10-10, Yotsuyasakamachi, Shinjuku-ku, Tokyo 160-0002, JAPAN
Telephone: +81 3 4335 9312 • Fax: +81 3 4335 9364
Email: bookimport@maruzen.co.jp • Web site: http://maruzen.co.jp

**RUSSIAN FEDERATION**
***Scientific and Engineering Centre for Nuclear and Radiation Safety***
107140, Moscow, Malaya Krasnoselskaya st. 2/8, bld. 5, RUSSIAN FEDERATION
Telephone: +7 499 264 00 03 • Fax: +7 499 264 28 59
Email: secnrs@secnrs.ru • Web site: http://www.secnrs.ru

**UNITED STATES OF AMERICA**
***Bernan Associates***
4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4391, USA
Telephone: +1 800 865 3457 • Fax: +1 800 865 3450
Email: orders@bernan.com • Web site: http://www.bernan.com

***Renouf Publishing Co. Ltd.***
812 Proctor Avenue, Ogdensburg, NY 13669-2205, USA
Telephone: +1 888 551 7470 • Fax: +1 888 551 7471
Email: orders@renoufbooks.com • Web site: http://www.renoufbooks.com

**Orders for both priced and unpriced publications may be addressed directly to:**
IAEA Publishing Section, Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

17-04721

International Atomic Energy Agency
Vienna
ISBN 978-92-0-101017-9
ISSN 1011–4289