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

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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.

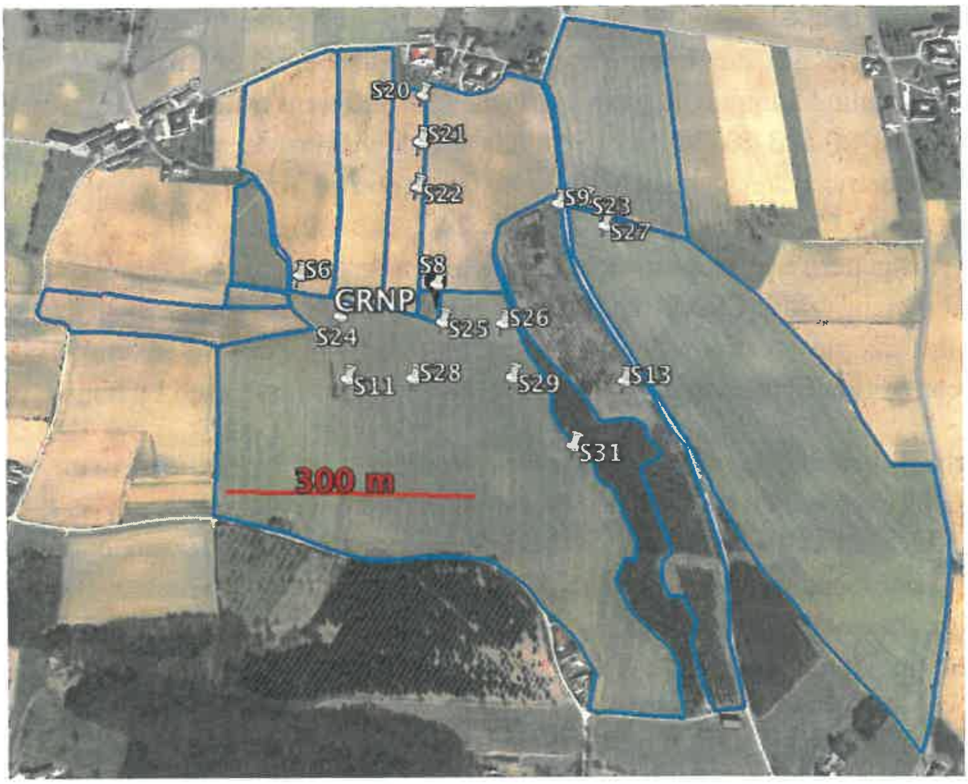

Fig.3.1. Location of 16 sites for soil moisture profiles (sensor measurement depths at 0-5 cm, 5-10 cm, 15-20 cm, and 45-50 cm) within the radial CRNS footprint[1].

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.

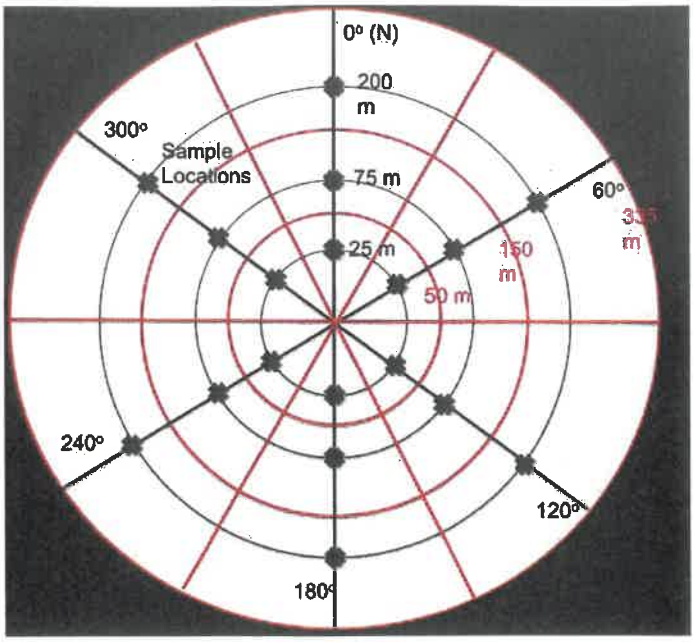

Fig. 3.4. Field sampling diagram. Black x marks denote sampling locations in the CRNS footprint. Each location is representative of an annular sector defined by red circles and radial lines. The area of each sector is inversely proportional to the sensitivity of the CRNS as a function of distance.

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].

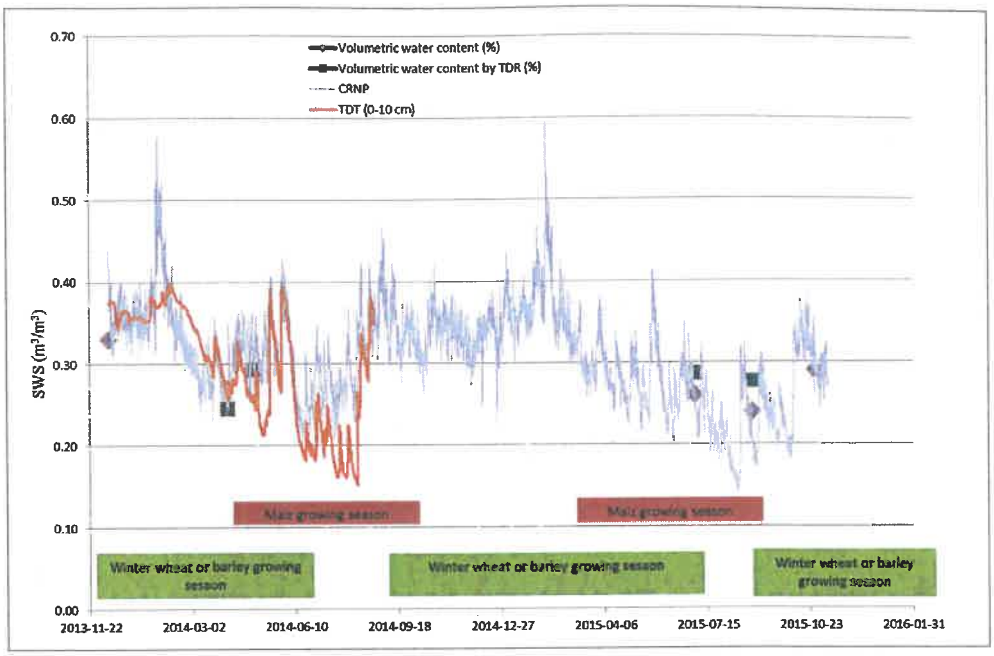

FIG.3.7. Time series of site average soil water content of TDT values at 0-10 cm depth, soil water content from the CRNS, and independent gravimetric (12 December 2013,and 3 July, 28 August and 28 October 2015) and TDR sampling campaigns (5 and 30 April 2014 and 3 July and 28 August 2015) at Petzenkirchen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

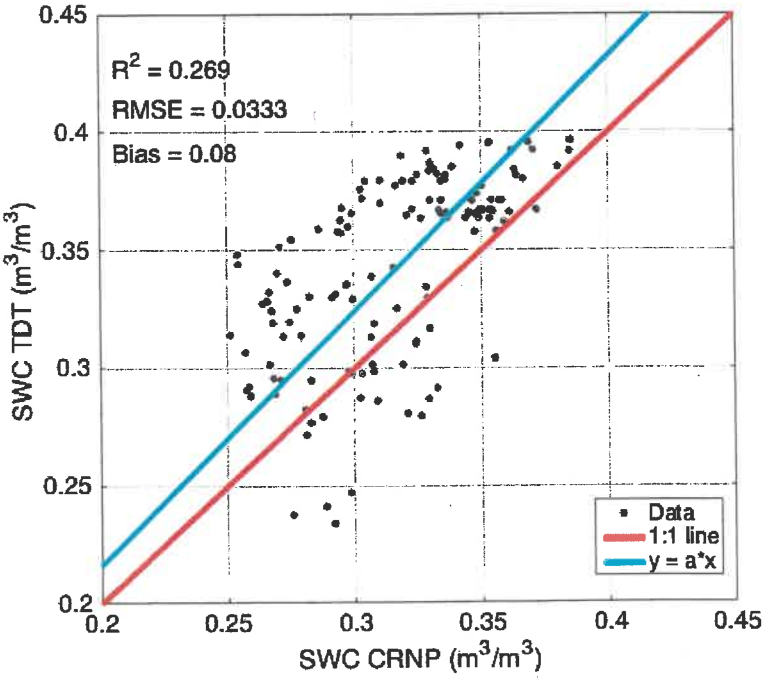

FIG. 3.8. Comparison of daily soil water content between the CRNS and independent TDT sensors (averaged from 0-20 cm) between 15 December 2013 and 1 May 2014. Note the RMSE is on the same order of magnitude (~0.033 m^3 m^{-3}) as the standard error of the mean (+/- 0.02 m^3 m^{-3}) of the TDT sensors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

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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

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Marketing and Sales Unit, Publishing Section
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Vienna International Centre
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1400 Vienna, Austria
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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..