Using a gamma-ray spectrometer for soil moisture monitoring: development of the the gamma Soil Moisture Sensor (gSMS)

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***Abstract*—A new type of soil moisture sensor has been developed that uses gamma-rays emitted by the soil to determine the soil moisture content. Natural radionuclides emit radiation that is detected by this gamma Soil Moisture Sensor (gSMS). Gamma-rays are attenuated by moisture in the soil and therefore the flux of gamma photons could act as a proxy for the amount of moisture present in the soil. Preliminary results show that the total gamma flux seen by the sensor is also influenced by variations in atmospheric radon concentrations. Therefore, the total gamma count cannot be used as a proxy for soil moisture and spectral analysis is needed to filter out the radon-induced noise and correlate the ^{40}K and ^{232}Th concentration with the soil moisture content. Static measurements have been initiated to determine the accuracy needed for establishing the soil moisture content variation over time.**

Keywords—Gamma-ray, Soil Moisture, Moisture Monitoring, gSMS, Full Spectrum Analysis

I. INTRODUCTION

A crucial part of water management for agricultural applications is the measurement of moisture concentration in the ground. Common methods used to measure the moisture content in soils are tensiometers, electrical resistance of the soil or by using Time Domain Reflectometry (TDR) [1], [2]. These methods can precisely estimate the soil moisture content at a specific point location in the soil, however it has been shown that the soil moisture content is highly heterogenous in both the spatial as in the depth distribution [3], [4]. Additionally, it has been established that point sensors need some time to settle to overcome the disturbance of the soil caused by placement of the sensor.

An alternative to the point measurement techniques is the use of cosmic-ray neutron sensors (CRNS) [5], [6]. These sensors have the advantage of measuring the response on moisture from a large volume of soil around the sensor. This technique does not only provide information on a much larger scale than the point measurements, it is also less prone to small-scale variations in the soil, since this will be averaged over the whole volume [7].

An even larger ground volume is “seen by” remote sensing techniques that use satellites such as the Sentinel-1 and Sentinel-2 missions. However, these satellites have a more coarse temporal resolution, low penetrations depth and have to be corrected for surface roughness issues [8]. And due to the large measurement volume they are of limited applicability for detecting small-scale variations.

Fig. 1: Schematic representation of the gamma Soil Moisture Sensor. The sensor measures gamma-radiation emitted by the soil under the sensor. If the moisture in the ground increases the amount of radiation is attenuated.

Gamma-ray spectrometers (GRS) measure the tiny amount of radiation emitted by natural occurring radionuclides which are present in all soils. M. Baldoncini *et al* have shown that the intensity of the gamma-radiation measured above an agricultural field directly correlates with the moisture present in the soil [9]. This technique measures radiation emitted by a large volume of soil and can be used to determine the average soil moisture concentration of this volume. Compared to point sensors, GRS measurements have the benefit of measuring a larger volume. However, this volume has a footprint in the order of meters which is much smaller than the footprint for CRNS measurements. In fact, the size of this footprint can be controlled by adjusting the measurement height of the sensor.

An additional benefit of GRS measurements it the flux of gamma-rays emitted by the soil, which is much larger than the detected neutron counts in a CRNS sensor as a result of cosmic rays [5]. The relatively high count rate of GRS measurements allow on-demand measurements while maintaining a low uncertainty.

In conclusion, GRS measurements could be used to collect soil moisture information with a spatial resolution that falls well within the size limits of a typical agricultural field.

To apply the GRS measurements successfully for measuring soil moisture on agricultural fields, some theoretical questions should be solved. Firstly, the sensors have to be calibrated such that the response of the sensor on soil moisture for a variety of soils is known. Secondly, it is known that the footprint of the sensor depends on the measurement height. Therefore, the exact relation of measurement height on the footprint should be known. And finally, it is expected that the presence of radon in air has a large effect on the measured signal. The effect of radon should be quantified. Besides the theoretical framework, a sensor should be developed that can be used autonomously for long term field measurements.

In this research a theoretical model and Monte Carlo simulations are used that describe and estimate the soil moisture content for various soil types and determine the footprint. These model calculations are validated with long-term stationary measurements to estimate the soil moisture content of a selected agricultural field.

II. THEORY

Natural occurring radionuclides ^{40}K, ^{238}U and ^{232}Th are present in the soil. The ratio and intensity of these nuclides are specific for each soil type [10]. The tiny fraction of these radionuclides present in the soil can be measured by using a gamma-ray spectrometer, which is a technique commonly used to characterize the geological origin of the rock, soils and sediments [11]. Spectrometers record gamma-ray spectra which are translated to radionuclide concentrations in the ground. The analysis procedure to translate the measured spectra to the absolute radionuclide concentrations incorporates environmental parameters such as the soil and air density, self-background of the measurement platform and the geometry of the measurement.

Stationary gamma-ray measurements measure within a constant geometry, however if moisture is added to the ground, the compound ground density (soil plus water) increases. The change in composition and increase in density leads to dilution of the gamma-rays detected by the spectrometer. An increase in soil moisture will decrease the counts per second measured by the detector. The radionuclide concentrations in dry soil remain constant, but the moisture will attenuate the gamma-ray signal. Effectively, the radionuclide concentrations “seen” by the sensor will decrease with increasing soil moisture content.

The amount of soil that contributes to the signal in the detector is determined by the environmental parameters: soil field bulk density, air density and the height of the detector above the field. An increase in detector height will result in a larger footprint (defined as the section of soil that emits gamma-rays that could reach the spectrometer). At the same time the increase in height will result in a bigger layer of air between the soil and the sensor, which causes more attenuation of the gamma-rays. The volume and shape of the soil that contributes to the signal in the detector is analytically modeled in [12], [13] and was verified by radiation transport calculations using Monte-Carlo simulation techniques.

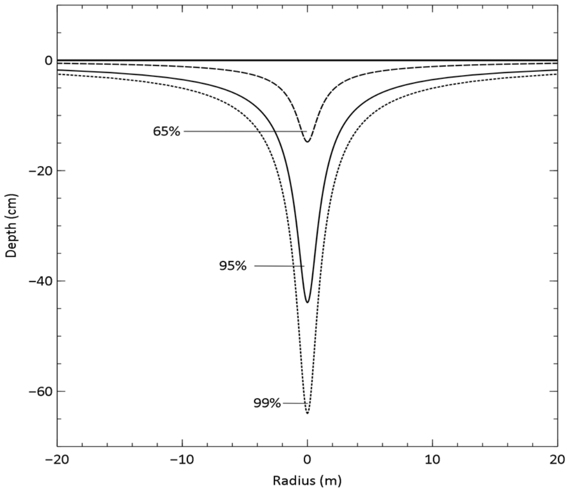

Fig. 2: Cross sections of the ground showing the origin of the radiation that gives 65%, 95% and 99% of the intensity (gamma energy 2.62 MeV, ground density of 1.8 g/cm^3 (1.5 g/cm^3 SiO_2 and 0.3 g/cm^3 H_2O)) for when the detector is placed at 80 centimetres above the ground. Schematic picture taken from [13]

A schematic cross section of the contributing soil when the detector is placed at 80 cm above the soil is shown in Fig. 2. Two observations about the origin of gamma-radiation result from this figure. Firstly, 99% of the gamma-rays originating from directly below the detector provide information up to 65 cm deep. Secondly, this depth resolution quickly falls off with increasing radius. Outside the radius of 10 m, only the top 5 cm of soil contributes significantly to the signal in the detector. Since the detector is unable to distinguish the origin of the gamma-rays, an average concentration of this depth distribution is measured.

Fig. 3: Medusa and Dacom sensors placed in a potato field in the north-east of the Netherlands. The black tube with the blue caps is the *gSMS* and the yellow sensors in the background are the Dacom TerraSen moisture sensors.

III. METHODS

The stationary measurements have been done using a new type of detector, a gamma Soil Moisture Sensor (*gSMS*) developed by Medusa Radiometrics B.V. The sensor contains a 2x2inch CsI scintillation crystal coupled to a multichannel analyzer. An embedded microcontroller continuously records gamma-ray spectra which are analyzed to determine the ^{40}K, ^{238}U and ^{232}Th concentrations in real time. The sensor merges fifteen minutes of spectral data with data from the on-board pressure, temperature and a humidity sensor and saves it to an integrated flash drive. An internal modem connects the sensor to the internet through a cellular connection and automatically uploads the data to an online platform that visually presents the data to a user. The setup can be powered by using a 230V or it can be connected to a battery that is charged by a solar panel, making it a self-supporting system. Fig. 1 shows a schematic drawing of the *gSMS* setup.

One of the *gSMS* is placed in a potato field located in the north-east part of the Netherlands belonging to a farm that is part of the *national testing ground for precision agriculture* (*National Proeftuin Precisie Landbouw*) (Fig. 3). Next to the *gSMS* a *TerraSen* sensor developed by Dacom B.V. is placed. This sensor continuously measures the soil moisture at a depth interval of 10 cm up to 50 centimeter deep. The *TerraSen* includes a rain gauge that measures the local precipitation. Both values are used to correlate the radionuclide concentrations measured by the *gSMS* with the actual conditions in the field.

The *gSMS* and *TerraSen* sensors have been placed in the field on the 27th of May 2020, at the start of the growing season, when the potato plants just emerged from the ground. A gamma-ray survey of the area with a radius of 100 m around the sensors showed that the potato field has a homogenous, sandy soil type. A homogenous source is advantageous for detecting differences in radionuclide concentrations because a highly heterogenous source will have a non-linear response to the moisture content, which is hard to predict without knowing the exact spatial radionuclide distribution.

The *gSMS* measurements are analyzed by using Gamman spectral analysis software [14] using Full Spectrum Analysis (FSA [15]) to determine the radionuclide concentrations. FSA is the process of decomposing the measured gamma-ray spectra into the separate radionuclide components. The key parameters in FSA are the so-called standard spectra. These are spectra that represent the response of the detector if it would measure a pure source of ^{40}K, ^{238}U or ^{232}Th. These standard spectra are normalized to 1 Bq/kg and are used to calculate the activity concentrations of the measured spectra. The concentrations are the number of times each standard spectrum occurs in the combination of standard spectra that best fit the measured spectrum. The fitting procedure is based on a least square algorithm and can be rewritten to a matrix inversion that is computationally efficient to solve [15].

The standard spectra for the *gSMS* sensor have been derived by using Monte-Carlo simulations. The standard spectra have been validated by using the Stonehenge calibration facility, located at Medusa Radiometrics in Groningen [16], [17]. The Monte-Carlo simulations are specific for the measurement geometry of the detector. For the *gSMS* the response has been calculated when mounted on a pole at 1.30 m above the field.

A first step in the analysis will be made by looking at differential measurements of the gamma-ray signal. From this result an estimate of the variation of soil moisture content is made, without giving the absolute value of the moisture content. This method is chosen as a first step because by doing this, it is not necessary to know the precise environmental parameters such as radionuclide distribution and soil density. A second step is to translate the gamma-measurements to absolute soil moisture content, for this the literature on the translation of CRNS measurements to absolute soil moisture content will be consulted [18].

IV. RESULTS AND PRELIMINARY CONCLUSIONS

The *gSMS* has been developed and deployed in a potato field. The period 26th May – 4th of July was marked as a test period in which there was experimented with measurement time and uploading of the data. After the 4th of July the sensor was marked as stable and measured continuously in the radionuclide concentrations in the potato field.

At the start of the measurement the potato plants were approximately 30 cm high. The crops increased in size and the approximated maximum growing size of 80-140 cm was reached on the 13th of July. On the 11th of September it was observed that the potato plants already started wilting which meant a decrease in the above-ground biomass.
It was foreseen that that the water content of the changing biomass would influence the measurement. The change in biomass is slow, and initially only increasing in time. Because this factor is a slow varying component, it can be separated from the soil moisture in the ground which is varying up and down with rainfall and temperature.

The counts plot shown in Fig. 5 exhibit a daily periodic variation in the count rate. This variation is caused by a shift in the recorded energy range due to daily temperature variations. As a part of the FSA algorithm, the spectra are corrected for this variation and the resulting radionuclide concentrations shown in Fig. 6 do no exhibit this daily variation. Besides this daily variation there are clear spikes present in the total counts plot that seem to coincide with rainfall. This observation is probably caused by the radon (^{222}Rn) radionuclides that are present in the atmosphere and are pushed down by the rain [11], [19].

Radon is a daughter of the decay of ^{238}U-series and is a radioactive gas with a half live of 3.8 days. The sole origin of atmospheric radon is the decay of natural occurring ^{238}U. When this gas escapes from the soil, where it is generated, it can migrate away from the point of origin. Escaped radon gas can influence gamma-ray measurements.

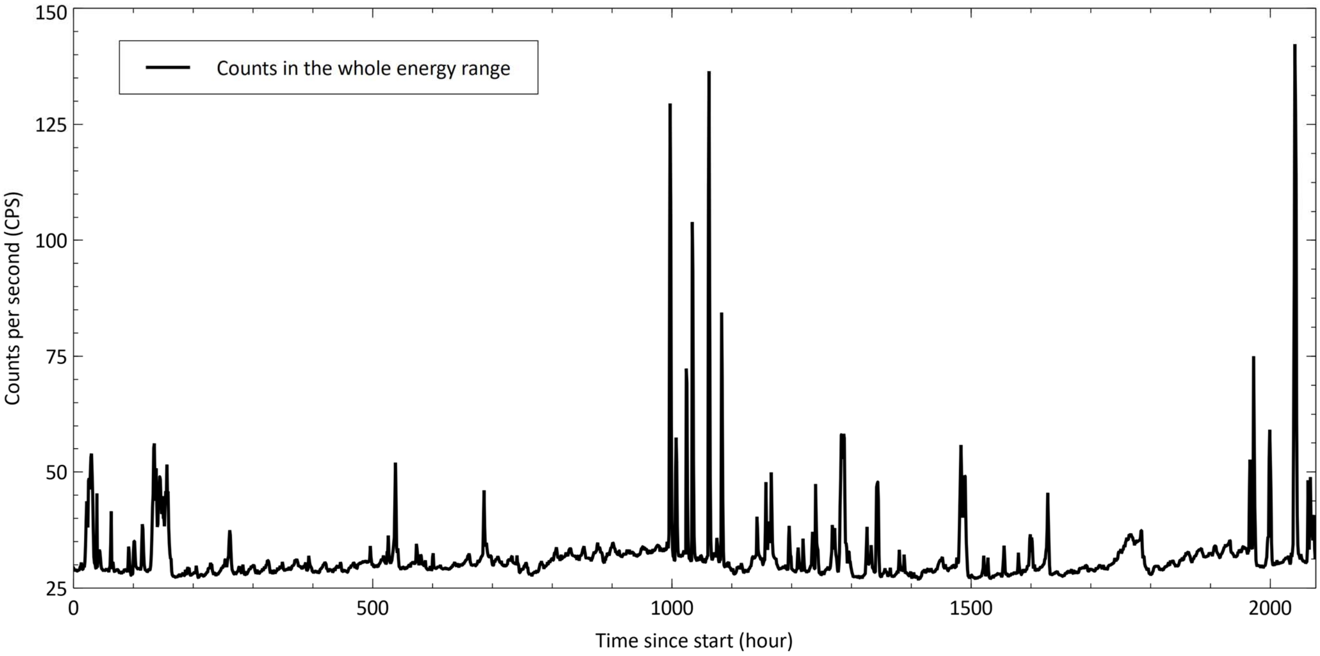

Fig. 5: Preliminary plot of the counts per second recorded by the *gSMS* in a potato field. The plotted points are the resulting counts per second, averaged over 1 hour of spectral data**.** A daily variation in the count per second an be observed. The peaks are a result of radon being pushed down in the atmosphere by rain. This radon influences will influence the resulting ^{238}U concentration and should not influence the ^{40}K and ^{232}Th concentration.

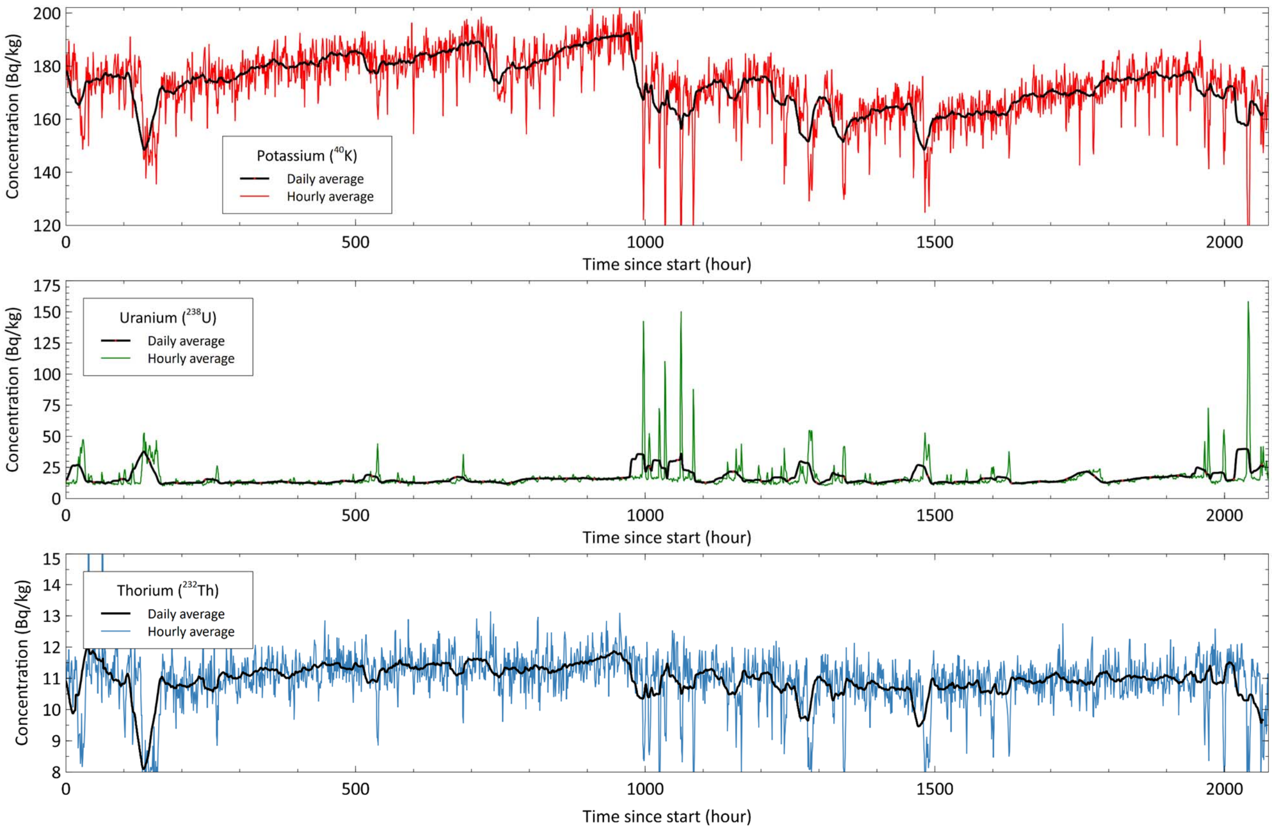

Fig. 6: Preliminary radionuclide concentrations recorded by the *gSMS* in a potato field. The plotted points are the resulting concentrations of 1 hours summed spectral data**.** The black lines are the daily moving average concentrations.

The amount of radon present in the atmosphere is a complex interplay of atmospheric and geophysical properties of the surrounding area, which makes it difficult and tedious to predict accurate concentrations. The concentration is, among others, dependent on the local pressure and temperature, the wind direction, the surrounding soil compositions to name just a few. Peaks in radon concentration are an indication of rainfall, but the absence of this peak does not mean that there is no rainfall.

In gamma-ray measurements on natural radionuclides, these ^{222}Rn radionuclides show a peak in ^{238}U concentration because the measured spectrum is almost identical. Only 3.6% of the detected uranium intensity originates from the decay chain before radon.

The spikes in the count rate are not caused by soil moisture changes and therefore it is concluded that spectral analysis is needed to separate the changes in count rate, due to radon, from the changes due to soil moisture variation. Full Spectrum Analysis will separate ^{222}Rn (as ^{238}U) from the more stable radionuclides ^{40}K and ^{232}Th, whose concentrations are expected to only vary with soil moisture. There is no component in the decay chain of ^{40}K or ^{232}Th that can influence a natural gamma-ray measurement and produce erroneous radionuclide concentrations in the soil.

Preliminary radionuclide concentration results of the *gSMS* measurements, shown in Fig. 6, indicate that there are variations over time of ^{40}K, ^{238}U and ^{232}Th concentrations. It is clear that the ^{238}U concentration shows large spikes in concentration that coincide with the spikes in count rate, as expected for the influence of radon.

The decay of ^{40}K consists of a single gamma-energy at 1.46 MeV, whereas the decay of ^{232}Th consists of a decay chain among which a high energy gamma at 2.62 MeV. Higher gamma-ray energies have a lower attention constant, which means that higher energies can penetrate through thicker layers of soil (and thus come from deeper). This energy difference suggests that the ^{40}K and ^{232}Th concentrations give information about different soil depths.

The daily average concentration of ^{40}K and ^{232}Th concentrations, shown in Fig. 6 indicate that the variation in the 1 hour radionuclide concentrations diminishes by summing the whole day. There are clear steps present in the ^{40}K concentration, which coincide, but less obvious, in the ^{232}Th concentration plot. As an example, this data suggest that soil moisture would be increased at 1.000 hrs after start of the measurement.

Further analysis and comparison of the radionuclide concentrations with the precipitation and point soil moisture measurements has to quantify correlation between the decrease in ^{40}K and ^{232}Th and the soil moisture content.

To test how GRS measurements can successfully be used for measuring soil moisture on agricultural fields, a first step is made: A sensor is developed that can measure autonomously, store data an transmit data to a server. This sensor is calibrated to measure absolute concentrations of radionuclides. The footprint of the sensor is determined with a theoretical model and Monte Carlo simulations. Full spectrum analysis was used to estimate the presence of radon in air and to determine a variation over time of the concentrations of ^{40}K and ^{232}Th.

Long-term stationary measurements were used to determine temporal variations of these radionuclides. At the time of writing the growing season has ended and the potatoes in the field have been harvested. However, soil moisture measurements and the precipitation as recorded by a local weather stations and the Dacom sensorss, were not yet available for a thorough analysis by comparing the *gSMS* data with these moisture measurement. This means that currently no final conclusion can be drawn about the correlation between the radionuclide concentrations and the soil moisture content.

However, as an outlook, it should be noted that if the results of the correlation between radionuclide concentrations and soil moisture are acute, a next step in the determination of soil moisture by using gamma-rays can be made. Sufficiently accurate gamma-measurements obtained by mapping the area with a quad or UAV, could be used to predict the soil moisture content. Both methods provide the flexibility of measuring the soil moisture distribution in an entire field, which is a great improvement over the conventional point measurements and the stationary gamma measurements. Additionally, the UAV method provides a method that is non-intrusive and does not cause any disturbances to the field.

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Live measurements can be seen on:
https://gsms.medusa-online.com with
username: guest@medusa-online.com, and
password Demo01

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