Chapter 6 : Effects of soil moisture in UAV-borne mapping studies

Development of the gamma Soil Moisture Sensor (gSMS)

6.1 Introduction

Moisture in the soil can influence radiometric measurements by attenuating the gamma rays. An increase in soil moisture will decrease the gamma-ray flux, resulting in lower radionuclide concentrations if left uncorrected. This chapter aims to characterize the influence of soil moisture on the gamma-ray flux, which can be used to correct gamma-ray measurements and determine absolute radionuclide concentrations in the soil, regardless of moisture level.

Not only does the soil moisture affect the gamma-ray flux, but the moisture concentration in the soil is also a crucial parameter for accurate water management in agricultural applications and therefore is of great interest to monitor it. Common point measurement techniques to determine the moisture content in soils are tensiometry and Frequency or Time Domain Reflectometry (FDR/TDR) (Ling, 2004; Werner, 1992). These methods estimate the moisture content at a specific location in the soil in a volume[3] of only ~0.014 m^3. This moisture content is usually not representative of much larger volumes as it has been shown that the soil moisture content is highly heterogeneous both horizontally and in depth (Rabot et al., 2018; van den Akker et al., 2007). Additionally, invasive point sensors, such as the examples given, need some time to settle to overcome the disturbance in the soil caused by the placement of the sensors.

In contrast to point measurements, cosmic-ray neutron sensors (CRNS) (Stevanato et al., 2019; Vather et al., 2018) measure soil moisture within a large volume, up to tens of hectares around the sensor (volume ~ 700000 m^3)[4], and therefore provide volume-integrated information. Consequently, this information is less prone to small-scale variations in the soil (IAEA, 2008). Furthermore, CRNS sensors can be applied to measure moisture at places other than the soil, such as the canopy of trees or bodies of water.

Remote sensing techniques that use satellites such as the European Space Agency's (ESA) Sentinel-1 and Sentinel-2 measure an even larger soil volume. However, these satellites have a more coarse temporal and spatial resolution, low penetration depth (< 5 cm) and the data has to be corrected for surface roughness (Lee and Walker,

[3] Assuming a sphere that has a radius equal to the maximum range of 0.15 m (Qin et al., 2021).
[4] Assuming a footprint radius of 660 m and measurement depth of 0.5 m (Zreda et al., 2012).

2020; Schönbrodt-Stitt et al., 2021). These satellites' 100 m spatial resolution makes them less suitable for measuring moisture variation within an agricultural field (Gao et al., 2017).

Gamma-ray spectrometers for geophysical applications measure radiation emitted by naturally occurring radionuclides present in all soils. Moisture in the soil will attenuate this gamma-ray signal. Baldoncini et al. (2019) have shown that the gamma-ray flux above an agricultural field directly correlates with the moisture concentration in the soil. Compared to point sensors, gamma-ray measurements determine the average moisture concentration over a larger volume, typically in the order of tens of cubic meters, which is much smaller than for CRNS measurements or Sentinel satellites. Moreover, the volume over which the gamma-ray spectrometer determines the moisture content can be controlled by adjusting the measurement height of the sensor.

Compared to the CRNS, the gamma-ray method has a smaller footprint which makes it possible to detect moisture variations within the perimeter of a typical agricultural field. Furthermore, the detected count rate induced by the flux of the gamma rays emitted by the soil is much larger than the detected neutron counts in a CRNS sensor due to cosmic ray induced neutrons (Stevanato et al., 2019). The relatively high count-rate of gamma-ray measurements allows on-demand measurements while maintaining a low uncertainty. Additionally, if the spectrometer is installed at sufficient height, the variation in moisture stored in above-ground biomass, such as in the canopy of trees, can also be extracted from these gamma-ray flux measurements. And finally, unlike CRNS measurements, gamma-ray measurements use the signal coming directly from the soil and therefore do not need to correct for a changing source term.

In conclusion, the absolute radionuclide concentrations resulting from gamma-ray measurements are influenced by soil moisture. But more interestingly, these effects could be used not only for correcting radionuclide measurements in the soil, but also to collect soil moisture information with a spatial resolution fitting the size of a typical agricultural field or a forest, extending the toolbox of commonly used hydrological sensors as shown in Fig. 6.1. However, to use gamma-ray measurements for moisture determination, the change in gamma-ray flux as a function of the moisture and by other potential influences has to be characterized. This chapter mainly focuses on the moisture in the soil, and it is noted that the concepts can be extended to moisture measurements in forestry and nature management studies.

6.1.1 Implementation of a gamma soil moisture sensor

To derive the soil moisture content from the signal of a gamma-ray spectrometer, three aspects that influence the gamma-ray flux in soil moisture measurements have to be considered:

Firstly, the sensors have to be calibrated to obtain the soil moisture as a function of gamma-ray flux. The calibration also has to characterize the other parameters that can influence the gamma-ray flux, such as soil density and mineral composition, atmospheric conditions (e.g. humidity and air pressure), and water that is stored in biomass, the amount of which obviously changes during a growing season. The gamma-ray flux will decrease as a function of soil moisture because when H_2O is added to the soil, the attenuation increases while the concentration of radionuclides in the soil per unit of mass is decreasing.

Secondly, the footprint of the sensor depends on the measurement height. Therefore, the exact relation between measurement height and the footprint should be known for a specific sensor. Sensors in an agricultural field are typically placed at heights up to a few meters, while sensors that aim to measure the moisture stored in a forest canopy are placed at the same height as this canopy, which can be as high as 28 m (Andreasen et al., 2021). For both these height ranges, the model presented in Chapter 3 can be used to determine the size and depth of the footprint.

Finally, the influence of atmospheric radon on the gamma-ray flux has to be studied and if possible, quantified. From geophysical gamma-ray measurements it is known that radon in the air can result in erroneously ^{238}U concentrations. This impact of this effect on stationary gamma-ray measurements is investigated.

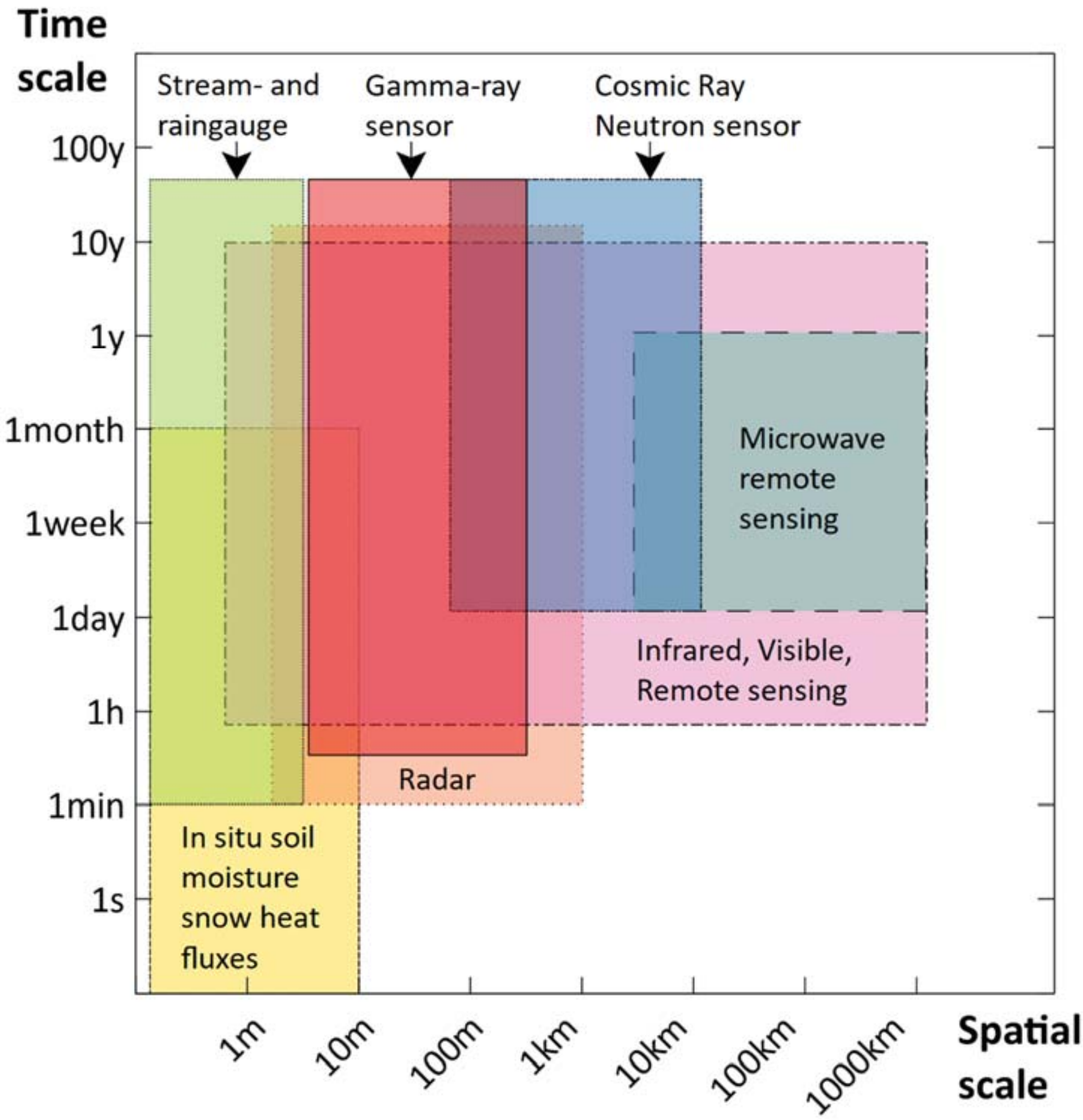

Fig. 6.1. Spatial and temporal scales of hydrological measurements. Figure adapted from (Gentine et al., 2012) and extended with gamma-ray and Cosmic Ray Neutron sensors. This figure shows on what scale the gamma-ray sensor operates compared to the other known soil moisture measurements. The y-axis represents the time scales where these moisture monitoring techniques are applied. E.g. flood forecasting studies require short time scales, whereas climate change models need the moisture content in the environment over a longer time. Note that this figure shows the characteristics of the measurement techniques and does not include limitations introduced by the measurement platform, nor does it compare the accuracy and depth of the various techniques.

6.1.2 Structure of this chapter

This chapter starts with establishing a model that describes a method to determine the soil moisture content using gamma-ray flux measurements. This model is constructed by exploring the major influences on the gamma-ray flux in long-term static geophysical measurements. For each influence, a (sub)model is proposed, which is subsequently validated by Monte-Carlo simulations.

The model section is concluded with a methodology on how to process gamma-ray data to establish the soil moisture concentration. This guideline covers the *physics* part of measuring soil moisture by using gamma-rays. The interpretation of the data and the implications for agricultural and forestry sciences is outside the scope of this chapter and remains to be studied, preferably in a multidisciplinary approach that combines the physics, geological and biological aspects of the gamma-based soil moisture measurements.

This chapter continues with a case study that uses a newly designed gamma-ray spectrometer, the gamma Soil Moisture Sensor (gSMS). This sensor was developed with the purpose of long-term outdoor measurements in remote fields. The case study presents data recorded with the gSMS sensor for seven months in an agricultural field.

6.2 Theory: Source of gamma-ray attenuation

This section describes the principles governing the measured gamma-ray flux resulting from the decay of naturally occurring radionuclides. The various aspects of the attenuation of gamma-rays in soil and air are explained, and potential influences on the gamma-ray flux in geophysical applications are listed and described.

The first aspect to be understood is the attenuation of gamma-rays and the influence of the medium through which gamma-rays travel. These general principles are then used to develop a model that accounts for the variation in measured gamma-ray flux due to soil composition (6.2.1), atmospheric conditions (6.2.2), biomass (6.2.3), radon (6.2.4), and the footprint (6.2.5). The section is finalized with a model that describes the change in gamma-ray flux as a function of soil moisture (6.2.6). To conclude, a list of parameters is presented that may significantly change the gamma-ray flux and are thus relevant to consider in gamma soil moisture measurements.

Throughout this chapter, two characteristic energy peaks present in measured gamma spectra due to the decay of naturally occurring radionuclides are used. These are the 1.46 MeV peak resulting from the decay of ^{40}K and the 2.61 MeV peak, which represents the highest gamma-ray emitted in the decay chain of ^{232}Th. These two gamma-ray energies are selected because they experience a different degree of attenuation (which is energy-dependent), and both peaks are clearly distinguishable in a typical spectrum that is recorded in agricultural or geophysical situations (and therefore only contains gamma-rays emitted by the decay of the naturally occurring radionuclides). In addition, on average, the higher energy gamma-rays originate from deeper sections in the soil.

6.2.1 Soil composition

The combination of composition and density of the soil is so different from place to place on earth that it has been compared to the fingerprint used in forensic sciences (Owens et al., 2016; Reidy et al., 2013). Fingerprinting in soil science is the term coined for the characterization of the composition of the soil. Fingerprinting is used to identify variations at the scale of a single agricultural field scale and to identify large regions with equivalent geological origin.

Because the soil composition is unique, the concentration and ratio of the naturally occurring radionuclides ^{40}K, ^{238}U and ^{232}Th in each soil are unique as well. This ratio is the core principle used in the radiometric fingerprinting of soils (Van der Klooster et al., 2011; Wijngaarden and Venema, 2002). The radiometric mapping of soil variations within a single field or the characterization of large geological areas is based on this radiometric fingerprint.

Some typical soil compositions are listed in Table 6.1. The intended purpose of this table is not to give an exhaustive overview of all the possible soil compositions. The purpose is to list typical mineral compositions and use this as an input to identify the mineralogical differences between soils. The mass fractions have been calculated for dry soil that contains no organic matter. Subsequently, these compositions are used to determine the minerals that typically make up the soil and calculate their influence on the mass attenuation coefficient of the soil.

Mass attenuation coefficients of soils

A gamma-ray spectrometer placed above the ground will detect gamma rays that are first attenuated by the soil and subsequently by the air, through which they travel. Equation (3.2) in Chapter 3 describes this process, and the soil and air composition are reflected in the density and mass attenuation coefficients μ_g and μ_a respectively. In geophysical tests that aim to measure the gamma-rays emitted by the decay of naturally occurring radionuclides, only the energy range 0.3–3 MeV is relevant. Using equation (2.5) and the mass attenuation coefficients for the individual elements, the mass attenuation coefficients of the soils listed in Table 6.1 have been calculated.

Fig. 6.2 shows the calculated mass attenuation coefficients for the range of 0.01 to 3 MeV for soils with the mineral composition shown in Table 6.1. In addition to these soils, the mass attenuation coefficient for pure SiO_2 is shown, and the inset figure shows a close-up of the range 0.3–3 MeV. The difference in the value for the mass attenuation coefficient between the various soil compositions and pure SiO_2 is < 1 % over the energy range 0.3–3 MeV. Therefore, using pure SiO_2 in soil moisture calculations is a very good approximation for all soils.

Table 6.1. List of mineral composition for a selection of typical dried soils. In the references listed at the top of the table, the mineral compositions of multiple samples are listed. This table shows the extreme values to give a range of the mineral composition that can be expected in soil samples spread across the earth (* this reference contains many soil sample compositions. This table shows compositions that have the lowest value for SiO_2, ** Mean values used (of 30 samples)).

Soil type	**Saudi clays**	**Jordanian sand**	**Korean Clay***	**Dutch Clay/Sand****
Reference	(Mohsen and El-maghraby, 2010)	(Alnawafleh et al., 2013)	(Zhang et al., 2006)	(Koenen and Griffioen, 2016)
Mineral composition	Mass fraction (%)	Mass fraction (%)	Mass fraction (%)	Mass fraction (%)
SiO2	62.46	98.38	46.74	71.48
Al2O3	18.40	1.32	39.30	13.09
Fe2O3	10.47	0.03	7.33	5.67
MgO	2.87	0.01	0.94	1.76
K2O	2.11	0.01	3.56	3.05
CaO	1.25	0.06	0.07	3.12
TiO2	1.08	0.18	1.07	0.76
Na2O	0.79	0.01	0.99	0.90
P2O5	0.39	0.00	0.00	0.16
MnO	0.17	0.00	0.00	0.02

The mass attenuation coefficient curves for the various soil compositions are almost identical because the shape and absolute value of the mass attenuation coefficients for almost all elements that appear in the soil are very similar in shape and absolute value in the energy range mentioned above (Fig. 6.3). This similarity is especially the case for oxygen, aluminium and silicon, which have the most significant mass fraction in the soil. No differences larger than 4 % (w.r.t. oxygen) are found in the energy range 0.3–3 MeV. The only element with a significantly different attenuation curve in this energy range is hydrogen (Fig. 6.3) due to its different gamma-ray interaction properties[5]. Therefore, a simplified model of the mass attenuation coefficients in soils can be expressed as a hydrogen term and a soil term. The former

[5] Hydrogen has a different electron to nucleon ratio, a different Z/A ratio which results in mass attenuation coefficient that is a factor two larger for Compton interaction. Additionally the photoelectric effect is a factor 10^{-4} smaller, and the pair-production is 36 times smaller for hydrogen than for oxygen.

scales with the amount of water in the soil, and the latter contains the soil composition. However, for clarity, in this research, the soil composition is split into the SiO_2 and H_2O components. The difference in these components is one of the parameters employed in measuring soil moisture by using gamma-rays. Note that all soils contain mass fractions of organic matter ranging from 3–6 % (agriculture) up to 15 % (peaty soils). In this research, gamma-ray measurements above agricultural soils are done. For simplicity, it is assumed that the amount of organic matter in these soils is small and, therefore, may be neglected.

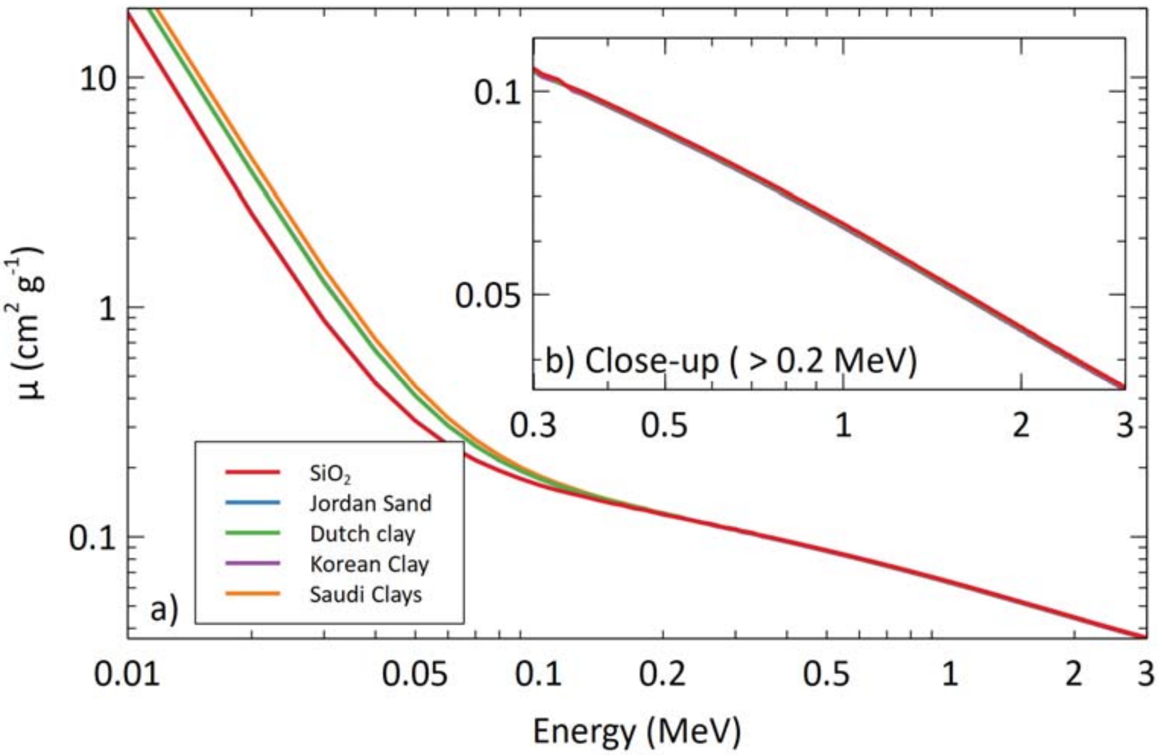

Fig. 6.2. The energy-dependent mass attenuation coefficients for the soil compositions that are listed in Table 6.1 and pure SiO_2. The curves have been calculated using the mass fractions of the elements present in the soil and calculating the mass attenuation coefficient of the compound by using equation (2.5). The inset shows a close up of the 0.3–3 MeV energy range relevant for geophysical gamma-ray measurements.

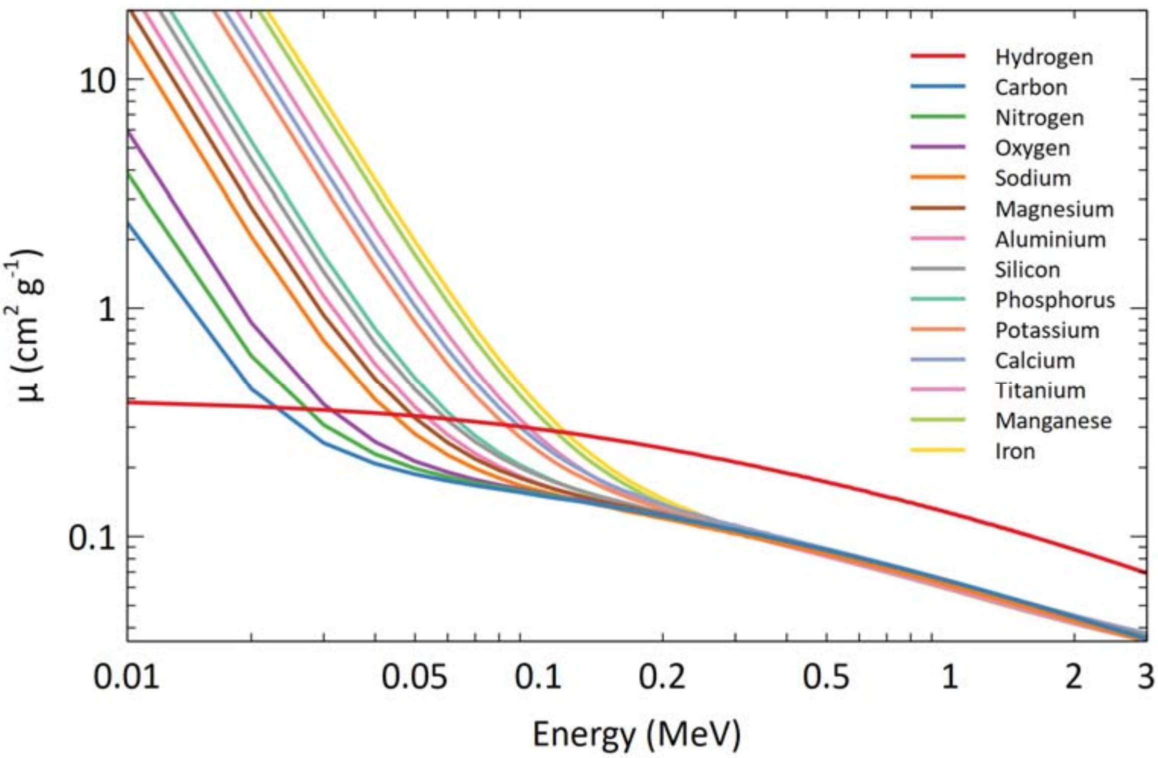

Fig. 6.3. The mass attenuation coefficients as a function of energy for a selection of elements commonly found in the soil. (Data retrieved from (Hubbell and Seltzer, 2004)).

Soil density

The heterogeneity of soils across the earth is reflected in the mineralogical composition and the density of the soil. The composition and history of the soil determine this density. As presented in the previous section, the soil varies in elemental composition. In addition, the soil comprises many solid particles that vary in size and density. Usually, there are pores between the solid particles, which can be filled with air or water, that facilitate the interaction between the soil and the environment (Rabot et al., 2018). In soil science, the following types of densities and space between the soil grains are defined:

Specific Density (SD) is the ratio of the mass of oven-dried soil[6] to the grain volume of the soil, which excludes the volume of the pores.
Soil (dry) Bulk Density (dBD) is the ratio of the mass of oven-dried soil to the bulk volume of the soil, which includes the pore space between the soil particles.

[6] Usually defined as mass after 24-48 hours while kept at 105 °C (see (IAEA, 2016))

Field Bulk Density (fBD) is the ratio of the mass of soil to the bulk volume of the soil, which includes the moisture content and the pore space between the soil particles (dBD + moisture content).

Porosity (ϕ) is the percentage of the soil volume occupied by pore spaces. Pore spaces can be filled with air or water. When pores are completely filled with water, the soil is saturated. For optimal crop growth, in agricultural fields, typically 60 % to 70 % of the pores are filled with water (Rabot et al., 2018).

In gamma-ray measurements, the gamma-ray flux is determined by the field bulk density (fBD). The field bulk density is expected to vary between the minimal (dry bulk density: dBD) and the maximum (dry bulk density: dBD + porosity filled with water). In a simplified soil model, the mineral composition has a specific density of 2.65 g cm^{-3}, which is the density of pure SiO_2. By measuring the soil bulk density and assuming such a simplified soil model, it is possible to estimate the amount of pore space.

Typical soils have a dry bulk density varying between 1.2 and 1.8 g cm^{-3} (Baldoncini et al., 2018; Schierholz et al., 2020). A specific density of 2.65 g cm^{-3} results in a pore space ranging between 55 % and 32 %. This pore space range results in a maximum field bulk density of 1.58 and 2.03 g cm^{-3}, respectively, when assuming a 70 % water-filled pore space. The increase in density due to soil moisture effectively decreases the radionuclide concentration (Bq kg^{-1}). The magnitude of this effect is the main principle of gamma soil moisture measurements and is quantified at the end of this section. In the soil moisture measurements, the variation of the soil density over time is only caused by a change in soil moisture content.

In stationary gamma soil moisture measurements, the dry soil bulk density can be assumed to remain the same throughout the measurement if no cultivation takes place. Equation (3.2) shows that the soil density is present only as a constant term in the prefix of the equation. This prefix determines the magnitude of the intensity measured by the spectrometer, which is inversely proportional to the field bulk density. An increase in this density causes a decrease in the measured gamma-ray flux. This intuitively makes sense because the attenuation of gamma-rays is governed by the interaction with matter. The effect of a reduction in gamma-ray flux is solely due to the increase in soil water content.

6.2.2 Atmospheric composition

Water vapour correction

This section estimates the effect of water vapour in the atmosphere on the gamma-ray flux above the soil. In this section, we assume that the water vapour content varies between 0 and 23 g m^{-3} for dry and saturated air, respectively, the latter being the saturated moisture content when the air has a temperature of 25 °C. For the calculation below, the atmospheric composition of dry air (density of 1.225 kg m^{-3}) is estimated as 78.08 % N_2, 20.95 % O_2, 0.93 % Ar and 0.04 % CO_2 by volume. For water-saturated air, 23 g m^{-3} of H_2O is added to the dry air composition, which has a small impact on the elemental composition of the air. In estimating the mass attenuation coefficients, the two characteristic gamma-ray energies of 1.46 and 2.61 MeV are used.

Using the described compositions and densities and calculating the mass attenuation coefficient by following the methods described in section 6.2.1 for the two energies results in the values shown in Table 6.2.

Table 6.2. Mass attenuation coefficients for two characteristic energies for dry and water-saturated air.

Energy (MeV)	μ_a for dry air (m^2 kg^{-1})	μ_a for saturated air (m^2 kg^{-1})
1.46	$5.229*10^{-02}$	$5.240*10^{-02}$
2.61	$3.846*10^{-02}$	$3.854*10^{-02}$

The reduction of the full energy peaks as a function of detector height for the dry and water-saturated air for the two different energies are calculated by using equation (3.2) and the mass attenuation coefficients listed in Table 6.2. From this calculation, it is found that the difference at 40 meters height between dry and water-saturated is only 1.1 % for 1.46 MeV and 0.85 % for 2.61 MeV. These differences are so small that it is concluded that in gamma-ray soil moisture measurements where the detector is placed at a maximum of 40 m, corrections for the water vapour content of the air are not needed.

Atmospheric density fluctuations

This subsection estimates the influence of changing pressure and temperature on the gamma-ray intensity. Similar to the assessment of the effect of water vapour corrections, the reduction in full energy peaks is estimated using equation (3.2). But now by calculating the change in atmospheric air density (ρ_a) as a function of pressure and temperature. By using the ideal gas law, it is possible to calculate the density of a gas:

$$\rho_a = \frac{P_a}{R_a\, T_a} \tag{6.1}$$

In which ρ_a is the density of the gas (kg m^3), P_a is the pressure (Pa), R_a is the specific gas constant (J kg^{-1} K^{-1}), and T_a is the temperature (K). The subscript a is added to indicate that this gas-law is applied to the atmospheric *air* density. The specific gas constant for air is calculated by using the atmospheric composition of dry air listed in the previous subsection. Atmospheric moisture is not considered in this calculation since the change in density due to moisture in the atmosphere is at maximum 1.9 % (from dry to water-saturated air).

The atmospheric pressure is known to vary between 95 and 105 kPa at sea level, and the temperature is expected to vary between -10 and 30 degrees °C. These parameters are used in equation (6.1) to calculate that the air density can vary between 1.091 kg m^{-3} (950 kPa and 30 °C) and 1.390 kg m^{-3} (1005 kPa and -10 °C). Using these two extreme values in equation (3.2) for the prominent energies of ^{40}K (1.46 MeV) and ^{232}Th (2.61 MeV) gives us an estimate of the influence of these atmospheric parameters on the gamma-ray flux.

Fig. 6.4a shows the reduction in gamma-ray flux as a function of detector height for the two prominent energies and calculated densities up to a height of 40 meters. Fig. 6.4b shows the relative difference between the two extreme densities with a close-up of the difference in gamma-ray flux for the 0 to 3 m sensor height range.

These figures show that the effect of changing atmospheric pressure and temperature becomes increasingly important with sensor height. For the range below 2 m, this effect is small (< 1.3 %), but this effect becomes significant for larger heights and increases up to 12 % at 40 meters height.

This section concludes that atmospheric pressure and temperature can be neglected if the atmospheric conditions are stable. When there are significant fluctuations in the pressure and temperature, especially at larger detector heights, moisture prediction in the soil should include these influences. This can be done by adjusting equation (3.2), either by replacing the air density with the air density given in equation (6.1) or by replacing the height with the equivalent height as described in Nicolet and Erdi-Krausz (2003).

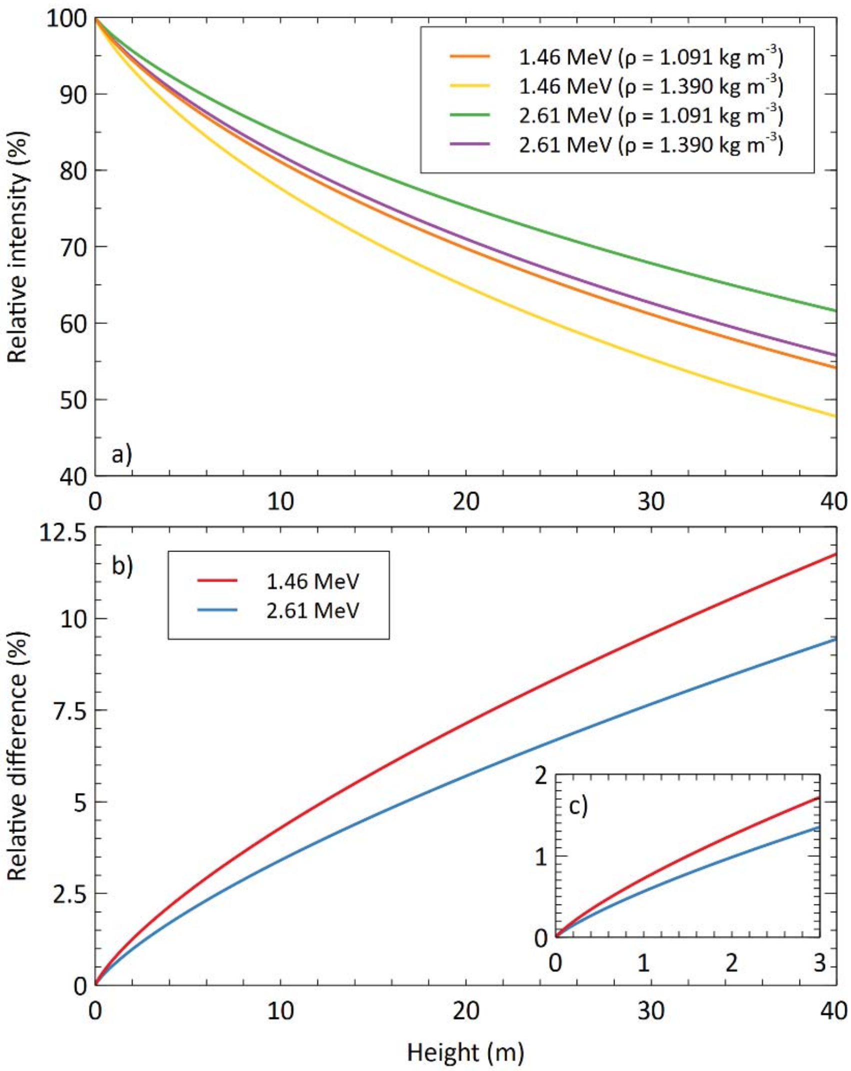

Fig. 6.4. The relative intensity of the gamma-ray flux for two different energies and extreme atmospheric conditions. a) shows the relative intensity of the measured gamma-ray flux and b) shows the difference in relative intensity between the atmospheric conditions for the two energies. c) is a close-up of b) in the 0–3 m height range.

Table 6.3. A selection of the amount of moisture present compared to the total biomass (under- and above-soil) as reported in the literature. The purpose of this list is to establish a range of moisture stored in biomass. It is found that agricultural crops have a higher percentage of water than forests. The moisture column (as mm moisture on top of the surface) has either been extracted directly from the literature or calculated on the assumption that 10 % (*), 25 % (**) or 30 % (***) of the wet mass is made up of other components than water.

	Wet mass (kg m^{-2})	Dry mass (kg m^{-2})	Moisture (mm)	Reference
Spring barley	0.89	0.13	0.75	(Andreasen et al., 2020)
Winter wheat	1.6	0.16*	1.44	(ten Harkel et al., 2020)
Sugar beets	3.8	0.95**	3.42	(ten Harkel et al., 2020; Zicari et al., 2019)
Maize	6.6	0.75	5.85	(Franz, 2021)
Tomatoes	Not reported		8.6	(Baldoncini et al., 2019)
European coniferous forest	22.7	12.5	10.2	(Andreasen et al., 2020)
Eastern US forests	10 - 15	3.0–4.5***	7.00–11.5	(Franz et al., 2013)
Western US forests	15 - 25	4.5–7.5***	11.5–17.5	(Franz, 2021)
Amazon rain forest	40 - 50	12–15***	28.0–45.0	(Franz, 2021)

6.2.3 Biomass corrections

When a crop or forest grows, it consists of a large amount of water. Yang (2015) measured various agricultural crops and reported dry masses to vary between 10 % and 14 % of the wet mass. Forests are known to have a lower relative moisture content (dry mass vs wet mass). The wood stumps of a tree have a dry mass ranging between 37 % and 55 % (Laurila, 2013), and leaves have a dry mass ranging between 30 % and 50 % (Huang et al., 2019). Table 6.3 lists wet masses for various crops and forests found in the literature. The dry mass column is extracted from the literature or is calculated based on a 10 % (*) or 30 % (**) estimation of dry mass. The amount of water is calculated by subtracting the dry mass from the wet mass and is expressed as a water layer in the moisture column of Table 6.3. Based on the values in Table 6.3, we will assume that, for agricultural applications, a maximum of 10 mm moisture is stored in biomass. For forests, this range can extend to 45 mm.

Theoretical model

To understand and estimate the contribution of biomass in the gamma soil moisture measurements, the magnitude of the change in gamma flux due to biomass should be known. An analytical approach, similar to the one presented in Chapter 3, is used to calculate this change. For simplicity, we neglect all non-water components of the biomass and reduce the biomass to a layer of water on top of the surface. Fig. 6.5 shows the schematic representation of this model.

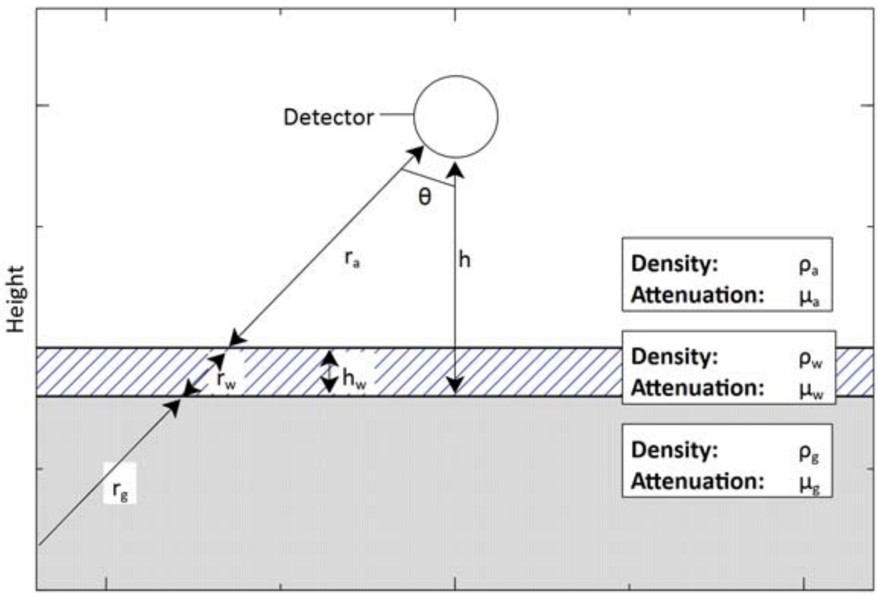

Fig. 6.5. Schematic representation of the analytical model represented by equation (6.2).

This model is based on Lambert's law with three independent terms (Ingle and Crouch, 1988) accounting for the attenuation in the soil, layer of water, and the air. An estimation of the full energy gamma-ray intensity that ends up in a detector when adding an extra layer of water on top of the soil can be calculated by integrating over the volume below the detector and is represented by the integral shown in equation (6.2).

$$I = \frac{A\epsilon\gamma}{4\pi} \int_{R_{min}}^{\infty} \int_{0}^{\frac{\pi}{2}} \int_{0}^{2\pi} \frac{1}{R^2} \, e^{-\mu_a \rho_a r_a} \, e^{-\mu_w \rho_w r_w} \, e^{-\mu_g \rho_g r_g} \, sin(\theta) \, R^2 \, d\varphi \, d\theta \, dR \qquad (6.2)$$

The symbols used in this equation represent the same physical quantities as in equation (3.2) and are described in section 3.2.1. The new parameters introduced in equation (6.2) are r_w, which is the distances the gamma-rays travel (m) in water which is dependent on θ, ρ_w is the density of water (kg m^{-3}) and μ_w is the mass attenuation coefficient of water (m^2 kg^{-1}). Integrating equation (6.2) results in:

$$I_{total}\,(h) = \frac{A\epsilon\gamma}{2\mu_g\rho_g} E_2[\mu_a\rho_a(h - h_w) + \mu_w\rho_w h_w] \qquad (6.3)$$

where E_2 represents the exponential integral of order 2 (Abramowitz and Stegun, 1970). Note that equation (6.3) is very similar to the reduction of full energy peaks presented in equation (3.2). The difference is an additional term in the argument of the exponential integral. Plotting equation (6.3) for the two prominent energies that result from the decay of the naturally occurring radionuclides ^{40}K and ^{232}Th and a layer of water up to 50 mm, which is equivalent to 50 kg of H_2O per m^2, results in the solid line in Fig. 6.6 The filled circles in the figure result from a Monte-Carlo simulation based on the geometry of the schematic model shown in Fig. 6.5.

From Fig. 6.6, we conclude that changing biomass volume has a significant influence on the measured gamma-ray intensity. This implies that in applications with changing biomass throughout the measurement (e.g. crop growth), the change in gamma-ray intensity cannot be considered to be solely due to soil moisture content variation. Biomass is a crucial parameter in the determination of soil moisture in agricultural applications since the purpose of agriculture is to increase biomass during the season. In forestry applications, it might be of influence only when the average amount of biomass changes throughout the measurement. Mature forests that exist in areas with little seasonal variation will have fewer changes in biomass than growing forests or areas where significant seasonal canopy changes occur.

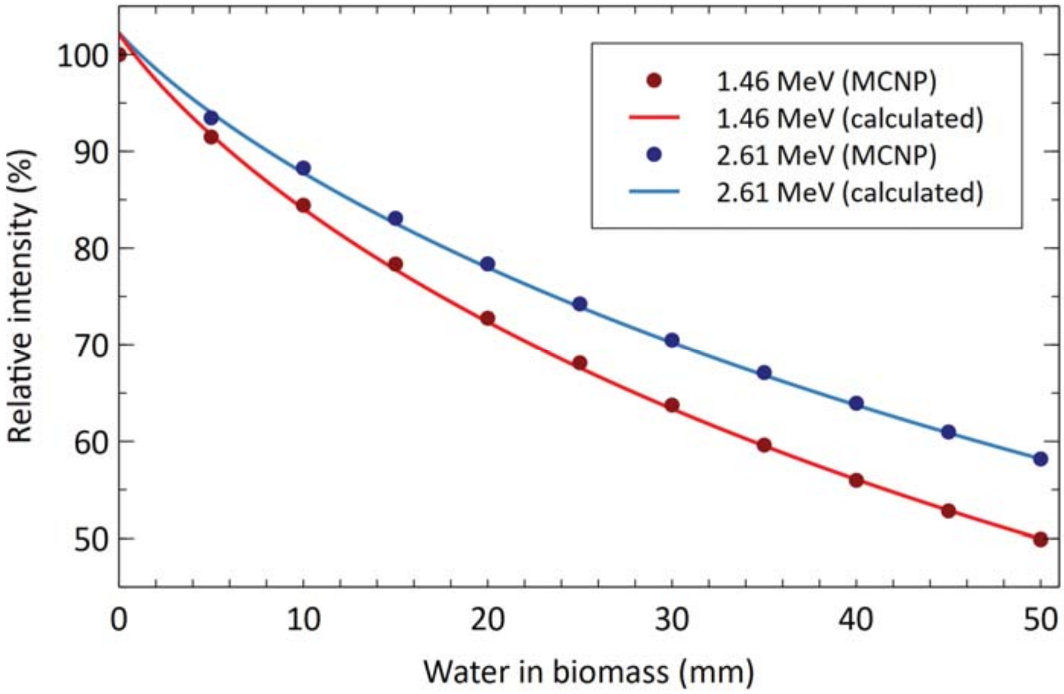

Fig. 6.6. The relative gamma-ray intensity measured by a detector as a function of the thickness of a water layer added on top of the soil for two different energies. The layer of water represents a simplified biomass model located between the source of gamma-rays (soil) and the detector. The solid lines are calculated using equation (6.3), and the filled circles in the graph result from a Monte-Carlo simulation.

6.2.4 Radon

An essential influence on geophysical gamma-ray measurements is radon (^{222}Rn). As described in Chapter 5, radon is a radioactive gas with a half-life of 3.8 days and is created in the decay chain of ^{238}U. This combination of properties allows radon gas to escape from the soil, where it is produced, and migrate into the atmosphere. Under normal circumstances, the concentration of this radon gas in the atmosphere is between 2 and 30 Bq m^{-3} (Oikawa et al., 2003; Porstendörfer, 1994; Sarrou and Pashalidis, 2003; Sesana et al., 2003; Smetsers and Bekhuis, 2021; Tchorz-Trzeciakiewicz and Kłos, 2017; Wenbin et al., 1990).

In Chapter 5, the dynamics of radon during geophysical gamma-ray measurements are discussed. One of the important conclusions of this chapter is that geophysical

Chapter 6

gamma-ray measurements should be done when the radon concentration in the atmosphere can be assumed to be homogenous. In section 5.2.3.1 of Chapter 5, it is stated:

This research assumes a constant ^{222}Rn concentration which is likely the case if gamma-ray measurements take place between 11 AM and 5 PM, not within three hours after rainfall (Charbonneau and Darnley, 1970; Nicolet and Erdi-Krausz, 2003), when there is some wind, preferable cloudy and the weather remains fair. A homogenous radon concentration distribution can be assumed to extend up to 1000 m around the measurement in both the horizontal and vertical plane.

However, stationary gamma-ray soil moisture measurements cannot adhere to this guideline. Gamma soil moisture sensors are intended to measure 24 hours a day for an extended period. Therefore, the conclusion is that during such measurements, there will be a fluctuation of the atmospheric radon concentration, which influences the measurements. As written in Chapter 5, the ^{222}Rn signal cannot be distinguished from the ^{238}U spectrum when the sensor is located close to the ground. The ^{222}Rn distribution during rain events cannot be assumed to be homogenous throughout the atmosphere. The increase in apparent ^{222}Rn concentration measured by the spectrometer is because decay products of the ^{222}Rn decay chain, ^{214}Pb and ^{214}Bi attached to atmospheric aerosols embedded in the rain droplets, are deposited on the ground surface. This surface source of ^{222}Rn will induce a differently shaped spectrum in the spectrometer above the surface compared to that of a homogenous radon cloud around the detector. Therefore, it is concluded that for the gamma soil moisture measurements, the derivation of moisture concentration in the soil should only be using the changes in gamma intensity originating from ^{40}K and ^{232}Th.

Although the ^{238}U concentration cannot be used for soil moisture determination, Bottardi et al. (2020) have shown that rain-induced changes in the γ-ray flux can be used to estimate the rain rate. This rain rate is a parameter that is strongly connected to the soil moisture concentration.

6.2.5 Footprint

The volume of soil containing the radionuclides of which the gamma-rays contribute to the signal in the gamma-ray spectrometer is called the footprint, and this is presented in detail in Chapter 3. This chapter describes how the extent of the footprint is dependent on the measurement height. Therefore, this footprint defines the volume in which moisture changes are reflected in the gamma-ray flux at the location of the detector. Consequently, this flux can be used as a proxy for the average moisture content in the footprint. Fig. 3.8 shows this footprint as a function of height. This figure indicates that in the height range of 0 to 20 m, the increase in footprint with detector height is sufficiently steep to use the height to control the volume for which the gamma-ray flux, and thus the soil moisture, is measured.

As described in Chapter 3, the contribution of gamma-rays as a function of distance does not have a discrete boundary; the farther away the gamma-rays originate, the smaller the contribution. However, for practical purposes in the following sections, the footprint is defined as the circular area from which 95 % of the gamma rays reaching the detector originate. For agricultural purposes, the gamma soil moisture detector is expected to operate in the 0.5–5 m height region and thereby covers an area of 0.03 to 1.1 ha, as shown in Appendix E.

6.2.6 Moisture in the soil

The purpose of the gamma soil moisture measurements is to quantify the amount of moisture present within the footprint of the spectrometer. In such measurements, the change in the gamma-ray flux over time reflects the soil moisture variation over time. The analytical model described by equation (3.2) is used to estimate the effect of moisture on the gamma-ray flux. For the estimation presented in this section, the detector height and atmospheric conditions are assumed to be constant, and the moisture is assumed to be distributed homogeneously throughout the soil. From these assumptions, it follows that the measured intensity of gamma-ray flux is entirely governed by the constant prefix of equation (3.2). A change in soil moisture is reflected in the density (ρ) and the mass attenuation coefficient (μ). The intensity changes as a function of soil moisture are then dependent on the changes in the density and mass attenuation coefficient due to changes in the soil moisture content.

The increase of moisture in the soil results in an increase in the field bulk density (ρ), and the addition of water increases the mass attenuation coefficient (μ) as described by equation (2.5) because $\mu_{H_2O} > \mu_{air}$. To estimate the reduction in gamma-ray intensity as a function of soil moisture, equation (3.2) is used, and the intensity is calculated for two energies (1.46 and 2.61 MeV) and three dry bulk densities (1.2, 1.5 and 1.8 g cm^{-3}) for the entire moisture range of 0–100 % pore-space filling, which result in a moisture content[7] value expressed in cm^3 H_2O cm^{-3}. Fig. 6.7 shows the relative gamma-ray flux as a function of volumetric soil moisture content.

From this figure, the following observations are made:

1. There is a significant reduction in the gamma-ray flux as a function of soil moisture content. For the densities ρ = 1.2, 1.5 and 1.8 g cm^{-3}, the relative intensity drops to 67 %, 76 % and 84 %, respectively, when all the pores are filled with water as compared to completely dry soil.

2. The lines for equal density but different energy are approximately equal (differences < 0.13 %). This leads to the conclusion that only the dry bulk density of the dry soil governs the relative reduction in intensity. This absence of an energy-dependent relative difference is because the ratio μ_{H_2O}/μ_{SiO_2} is approximately constant[8] for the whole energy range 0.3 – 3 MeV, and the figure shows the relative intensity changes.

3. The dry bulk density of the soil determines the pore space volume and, therefore, the maximum volumetric moisture content, which determines the slope and endpoint of the curve. Consequently, variation in intensity due to volumetric moisture content may also be used to determine the dry bulk density by fitting the data to the slope of the curve in the figure.

Conclusion

A reduction in the gamma-ray flux with a magnitude up to 16 % and 33 % for soils with a dry bulk density of 1.8 and 1.2 g cm^{-3} can be expected in the range between dry and water-saturated soil. Fig. 6.7 shows that the slopes of the curves shown are strongly dependent on the dry bulk density of the soil. Therefore, this subsection concludes that in estimating the absolute soil moisture levels, the dry bulk density should be known or measured. Alternatively, derivation of the soil density from long term measurements that include wet and dry periods is possible. The latter method

[7] This moisture content is a fraction, however the unit cm^3 cm-3, commonly used in literature, is used in this chapter.
[8] The difference compared to the average ratio in this energy range is < 1.5%.

only works if the dataset used to derive the slope contains the whole range of soil moisture saturation shown in Fig. 6.7.

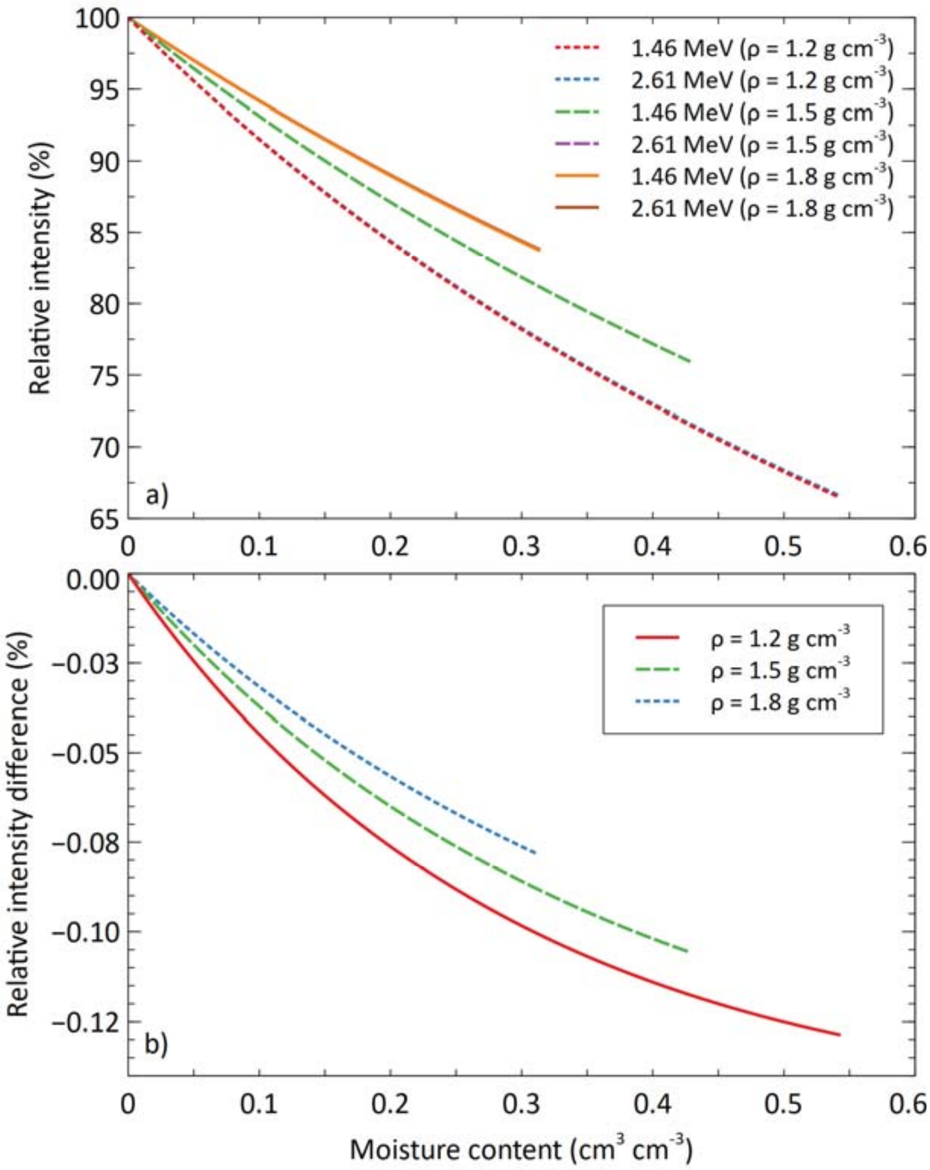

Fig. 6.7. a) Relative gamma-ray flux according to equation (3.2), as a function of volumetric moisture content in the soil for two energies and three densities. The relative intensities for equal densities and different energies almost coincide and appear as a single line, and the small difference is shown in b).

6.2.7 Conclusions on gamma Soil Moisture measurements theory

A gamma-ray spectrometer placed in a field at a stationary position will measure a gamma-ray flux due to the decay of ^{40}K, ^{238}U and ^{232}Th. A change in the amount of moisture in the soil is reflected in the gamma-ray flux. In addition to the soil moisture, flux changes can be caused by changing external environmental or atmospheric conditions. The preceding sections have discussed and estimated the most important sources influencing the gamma-ray flux in stationary measurements. Some external sources have an influence with a similar magnitude as the flux-variation due to soil moisture. Other external sources can be neglected. This finalizing subsection lists the conclusions from these preceding sections and describes the relevant external influences on the gamma-ray flux in gamma soil moisture measurements.

Based on the preceding sections, the following conclusions are drawn:

Soil composition: The mineralogical soil composition has negligible influence on the value of mass attenuation coefficients (section 6.2.1) in the relevant energy range of the gamma-rays. However, the soil dry bulk density is essential for soil moisture determination since this metric determines the magnitude of the relative intensity decrease as a function of moisture (section 6.2.6).

Atmosphere: Atmospheric conditions may be of importance, depending on the measurement height. It is always possible to neglect the amount of water vapour in the atmosphere. The pressure and temperature need to be accounted for and become increasingly important at larger measurement heights. The maximum effect is in the order of ~ 1 % at 1.5 m and ~ 2 % at 3 m and can become similar in magnitude as the soil moisture flux changes when exceptional atmospheric conditions occur when the detector is placed at an altitude of 40 m (section 6.2.2). Because the correction is straightforward, and the input parameters (pressure and temperature) are easy to measure, it is advised always to apply this correction.

Biomass: Biomass corrections are needed when the biomass around the sensor changes throughout the measurement (section 6.2.3). This is the case for moisture monitoring in agricultural applications, but also when seasonal changes cause changes to the forest canopy.

Radon: Radon will influence the shape and intensity of the recorded spectrum, reflected in the apparent ^{238}U concentration (section 6.2.4). Therefore, it is concluded that ^{238}U should not be used to determine the amount of moisture in the soil. Instead, only the flux as a result from ^{40}K and ^{232}Th should be used. Because ^{238}U should be omitted, Full Spectrum Analysis (FSA) is the preferred radionuclide analysis method. The window analysis method (Nicolet and Erdi-Krausz, 2003) commonly used to derive radionuclide concentrations will result in a larger uncertainty associated to ^{40}K due to the stacking of uncertainties (systematic error) and the decreased number of counts used in the analysis (statistical error). Potentially the flux changes due to ^{222}Rn decay products deposited by rain fall which can be used to estimate the duration and intensity of precipitation events or distinguish between precipitation and irrigation (Bottardi et al., 2020).

Sensor height: The height of the spectrometer determines the footprint of the gamma-ray signal (section 6.2.5). This sensor height can be used as a feature to select the footprint size and, therefore, the soil volume over which the average moisture concentration is measured. At the same time, this is also a limitation: only the average moisture content within the footprint can be determined. Because of this, the density and pore space of the soil in the footprint should be relatively homogenous.

Soil moisture: Considering the aforementioned conclusions, it is possible to measure a soil moisture variation beneath the detector (section 6.2.6). The combination of equations (3.2), (6.1) and (6.3) leads to a compound expression that describes the theoretical flux change due to soil moisture that includes the atmospheric conditions (pressure and temperature) and the presence of biomass. The ideal gas law of equation (6.1) replaces the air density (ρ_a) in this expression:

$$I_{total}\,(h) = \frac{A\epsilon\gamma}{2\mu_g\rho_g} E_2 \left[\mu_a \frac{P_a}{R_a T_a}(h - h_w) + \mu_w \rho_w h_w\right] \qquad (6.4)$$

Chapter 6

6.3 Experimental test

This section presents an experiment to explore the application of the model developed in the preceding section that describes the effect of soil moisture on the gamma-ray flux from the soil.

6.3.1 The gamma Soil Moisture Sensor (gSMS)

The gSMS (Radiometrics, 2020) is used for this experiment. This sensor contains a 2x2" (100 ml) CsI crystal intended to be used for long term stationary outdoor measurements. The sensor contains a multi-channel analyser that records 512 channel spectra. Counts collected in a time interval of 60 seconds are merged into a single spectrum, and a reading of the pressure, temperature and humidity are added. The resulting data is saved to the internal storage of the spectrometer. The spectrometer is powered by a battery that continuously recharges using a solar panel. The setup is shown in Fig. 6.8.

Fig. 6.8. Left: schematic drawing and picture of the gSMS sensor setup in the field. The black tube with blue caps mounted on a pole represents the gamma-ray sensor. The box on the ground is a schematic representation of the battery continuously recharged by the solar panel. In practice, this battery container is small compared to the measurement footprint so that it does not block a significant portion of the gamma-rays emitted from the soil. The blue wiggles in the schematic drawing represent the gamma radiation from the soil, measured by the sensor. Right: a picture of the setup in an agricultural field that is used to grow potatoes.

This experiment aims to derive the amount of moisture in the soil by using the changes in gamma-ray flux from derived ^{40}K and ^{232}Th concentrations. To enable the derivation of soil moisture from spectral gamma-ray data, the recorded gamma-ray spectra have to contain a sufficient number of recorded events (counts) to separate the ^{40}K signal from ^{238}U and ^{232}Th with an uncertainty that is lower than the changes in concentration due to soil moisture variations. The sensor is calibrated in a well-defined calibration setup (Van der Graaf et al., 2011) to obtain standard spectra so that radionuclides extraction is possible. The spectrometer's response to 1 Bq kg^{-1} of source material is a standard spectrum. This calibration allows the extraction of radionuclide activity concentrations by using Full Spectrum Analysis (FSA) (Hendriks et al., 2001). By using the Monte-Carlo procedure described in Van der Graaf et al. (2011), it has been established that the influence of soil moisture on the shape of the spectra is negligible. Typical radionuclide concentrations in agriculture fields are 500 Bq kg^{-1} of ^{40}K, 40 Bq kg^{-1} of ^{238}U, and 30 Bq kg^{-1} of ^{232}Th (Baba et al., 2004; Killeen et al., 2015; van der Veeke et al., 2021b). Using the calibration, we estimate that these concentrations result in count rates of 9.9, 10 and 8.8 cps for ^{40}K, ^{238}U and ^{232}Th, respectively. The concentrations' uncertainties are calculated using Poisson counting statistics and estimated to be smaller than 1 % for all radionuclides, provided that multiple consecutive readings are combined to a summed acquisition time larger than 15 minutes. This uncertainty is an order of magnitude smaller than the expected variation in relative intensity, as shown in Fig. 6.7, and therefore, the measured radionuclide concentrations can be used to monitor the soil moisture.

6.3.2 Moisture and rain sensor

The Dacom TerraSen pro (Dacom, 2020) (Fig. 6.9) is a point sensor used to measure the amount of moisture in the soil. The TerraSen is an FDR sensor that measures the dielectric permittivity in the soil at a depth-intervals of 10 cm to a maximum of 50 cm and converts this to soil moisture content. The sensor records the soil moisture content at each depth in mm H_2O per 10 cm at an interval of 1 hour and has a laboratory tested uncertainty of ± 2 % (C. Rijzebol (CropX), personal communication, March 3, 2022). It determines the soil moisture in a volume of approx. 0.014 m^3 at each measurement depth. A rain gauge with an aperture of 200 mm^2 and a resolution of 0.2 mm is used to measure the precipitation in mm per hour. The sensor is powered by an internal battery charged by a small solar panel attached to the sensor. This sensor is widely used in agricultural applications by CropX and used to steer the irrigation schedules throughout the growing season (CropX, 2022). A study by the University of Wageningen has found that this sensor has a high measurement accuracy and gives a good representation of the local moisture levels in the top 30 cm (Kool et al., 2022).

Fig. 6.9. Dacom TerraSen pro sensor. The probe on the bottom of the picture is inserted into the soil and contains the moisture sensors at five depths. The yellow cup on the top right of the stick is the rain gauge, and the solar panel on the top right is used to charge the sensors' internal battery.

6.3.3 Test site

The gSMS and TerraSen pro sensors were placed in an agricultural field (near the village of Onstwedde, in the north-eastern part of the Netherlands (coordinates: 53.00404° N 7.00438° E). This field consists of podzol soils composed of fine loamy sands that are high in organic content, and the soil has an estimated dry bulk density of 1.5 g cm^{-3} (source: Dutch Key Register of the Subsurface (BRO)). The gSMS sensor collected data between the 10th of May 2021 and the 12th of November 2021 at the height of 1 m. This height yields a circular measurement footprint with a radius of 17 m for the 95 % footprint, translating to a soil volume of 79 m^3 (Appendix E). On the 27th of May, the TerraSen sensor was placed two meters to the north-west from the gSMS. During the measurement campaign, the field was used to grow sugar beets, sown on the 20th of April 2021 and harvested on the 12th of November 2021. Throughout this growing season, the field was not irrigated. Fig. 6.10 shows two pictures made during the measurement campaign.

a) b)

Fig. 6.10. Pictures of the test site of the gamma-flux measurements on two dates during the measurement campaign. a) on the 27th of May, right after the placement of the TerraSen sensor. No sugar beet growth above the soil is visible. b) on the 13th of September, above-soil beet crops are visible.

6.3.4 Spectral data processing

In post-processing, 15 consecutive one-minute spectra collected by the MCA in the gSMS sensor are mapped to an energy scale by using the standard spectra, and then summed. The resulting energy spectrum is used to derive concentrations of ^{40}K, ^{238}U and ^{232}Th with FSA (Hendriks et al., 2001) by using the Gamman® software package (Medusa Radiometrics, 2012).

The calculated radionuclide concentrations are not corrected for atmospheric conditions (section 6.2.2) because the sensor is located at 1 m height, and the influence on the count rate of changing pressure and temperature is < 1 % (Fig. 6.4). Since the biomass of sugar beets was not monitored through the measurement campaign, the measured concentrations could not be corrected for the biomass.

Table 6.3 describes how sugar beets contain a maximum of 3.42 mm H2O. Fig. 6.6 shows that this amount of water causes a maximum gamma flux reduction of 5 %. This subsequently results in a maximum of 2.2 % reduction in the reported H_2O saturation percentage (Fig. 6.7). The moisture distribution in biomass is not a water layer on the surface, as is assumed in section 6.2.3. In reality, this moisture has a more complex distribution where some is stored in the sugar beets under the soil and some in the foliage above soil.

The measured ^{238}U concentration shows a clear and significant increase in concentration in coincidence with rain events. Rain causes a temporary decrease in ^{40}K and ^{232}Th concentration because of the large amount of H_2O present in and on the soil, which is not necessarily a good representation of soil moisture level after the rain has settled because not all moisture will be stored in the soil. All radiometric readings recorded while the ^{238}U concentration lies 15 % above the average of ^{238}U concentration have been removed. The average consecutive time period removed around each rain event, the time it rained plus the time needed for the uranium concentration to settle was found to be 188 minutes. For the subsequent analysis of moisture concentration in the soil, the ^{40}K and ^{232}Th concentrations are used.

On average, the concentration encountered in the field was 209 Bq kg^{-1} of ^{40}K, 13 Bq kg^{-1} of ^{238}U and 11 Bq kg^{-1} of ^{232}Th, which is smaller than estimated in section 3.1. Therefore, to mitigate the statistical fluctuations in radionuclide concentrations due to the stochastic nature of radioactive decay, the data is smoothed. A Savitzky-Golay filter (Savitzky and Golay, 1964) that has a window of 97 records (24 hours + 1 record) and a first-order polynomial was applied to the data. The intensity change as a function of soil moisture is described in equation (6.4) (which reduces to equation (3.2) when neglecting the atmospheric parameters and biomass). Fig. 6.7 shows that the intensity reduction as a function of soil moisture depends on the density of soil in the measured area and the radionuclide concentration when no moisture is present in the soil. This latter value is estimated by assuming that the smallest radionuclide value present in the measurement campaign dataset represents 100 % pore-space filling (moisture saturated soil), representing an intensity reduction of 76 % (Fig. 6.7). The intensity when no moisture is present can be derived from this value. The derivation of the calculation of moisture content from the radionuclide ^{40}K and ^{232}Th concentrations is presented in Appendix C (equation (C.11)).

6.3.5 Rain gauge data processing

The TerraSen moisture data at the five depths and rain gauge data is extracted from the sensor. Following advice from CropX (C. Rijzebol (CropX), personal communication, March 3, 2022), the moisture data from the top three sensors are summed to get the mm's of moisture present in the top 30 cm of the soil. The rain gauge data is used without additional processing. An additional soil moisture metric is created by estimating the accumulated moisture in the soil from the reading of the rain gauge by using the following equation:

$$M_i = M_{i-1} + RG_i - E_{soil} \tag{6.5}$$

in which M_i is the amount of moisture in the soil at time i in mm, RG_i is the reading of the rain gauge at time i in mm and E_{soil} is the soil evaporation rate in mm per time period i and is set to the average precipitation per time i during the measurement campaign. This value is determined by summing the amount of precipitation observed during the experiment and calculating the average precipitation per day, which is 2.16 mm day^{-1}. This estimation is of the same order of magnitude as the commonly found value of 1.5 mm day^{-1}, as reported by Small et al. (2018) and very close to the average of 2.34 mm day^{-1} reported by the Royal Dutch meteorological institute (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2021)[9]. M_0 is amount of moisture present in the soil at the start of the measurement and is estimated by overlaying the shape of the M_i trend over the ^{40}K concentration at the start of the TerraSen measurements. Note that this is a simplified model. E.g. the model neglects the counteracting effects of temperature and plant surface area, both known to influence the daily amount of evaporation.

6.4 Results

Fig. 6.11 shows the data collected by the TerraSen sensor (Fig. 6.11a and b) together with the soil moisture levels derived from the gSMS readings (Fig. 6.11c and d). Panel a) shows the soil moisture content in the top 30 cm as measured by the TerraSen sensor. The blue bars in panel b) show precipitation recorded by the rain gauge that is part of the same sensor. During the experiment (170 days), a total of 366 mm was reported by the rain gauge. It is observed that rain events coincide with an increase in soil moisture level. However, the amount of rain is not related to a proportional increase in soil moisture. An example of this observation can be found between 2021-09 and 2021-10. This period contains the largest readings of hourly precipitation, which is not proportionally reflected in the value for the soil moisture. Furthermore,

[9] Calculated by using the crop evaporation data measured by the weather station in Nieuw Beerta, located 22 km away from the measurement site. As prescribed by (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 2021), the evaporation data is multiplied by time and crop dependent factors reported in (Hooghart and Lablans, 1988).

at the far right of the graph, the moisture sensors report a steady increase without precipitation being reported by the rain gauge.

Fig. 6.11c and d show the moisture level in the soil calculated by using the ^{40}K and ^{232}Th concentrations measured by the gSMS, as described in Appendix C and D. The apparent ^{40}K concentration data has a minimum and maximum of 171 Bq kg^{-1} and 204 Bq kg^{-1}, respectively. The apparent ^{232}Th concentration has an minimum of 10.5 Bq kg^{-1} and a maximum of 12.1 Bq kg^{-1}. It is observed that radiometric based soil moisture of ^{40}K (red line) and ^{232}Th (dark blue line) and the precipitation based moisture estimated moisture in the soil (black line) are very similar in shape and thus indicate a proportional response of the gSMS to the amount of precipitation. However, there are points where both lines do not show comparable results. Around the 2021-09 point, the ^{40}K and ^{232}Th curves show several increases in soil moisture, whereas the blue bars and black lines do not show precipitation. Furthermore, the far right of the figure shows a steady decrease in the precipitation based moisture, although the radiometric based moisture percentage (red and dark blue lines) display an increase. Finally, it is found that the soil moisture calculated by using the ^{232}Th concentration reveals more short-term variation than when using the ^{40}K concentration.

Comparing the TerraSen based soil moisture readings in Fig. 6.11a to the radiometric based moisture readings in Fig. 6.11c and d reveals some similarities on a short time scale (increases that may coincide with rain events) but no correlation on a long time scale. Both the TerraSen (green line) and gSMS (red and dark blue lines) moisture data show a direct response to precipitation. However, the TerraSen soil moisture data (green line) shows a gradually declining value to its minimum around 2021-10, after which it steadily increases, whereas the gSMS data shows a minimum moisture level between 2021-6 and 2021-7, after which it gradually increases until the end of the measurement.

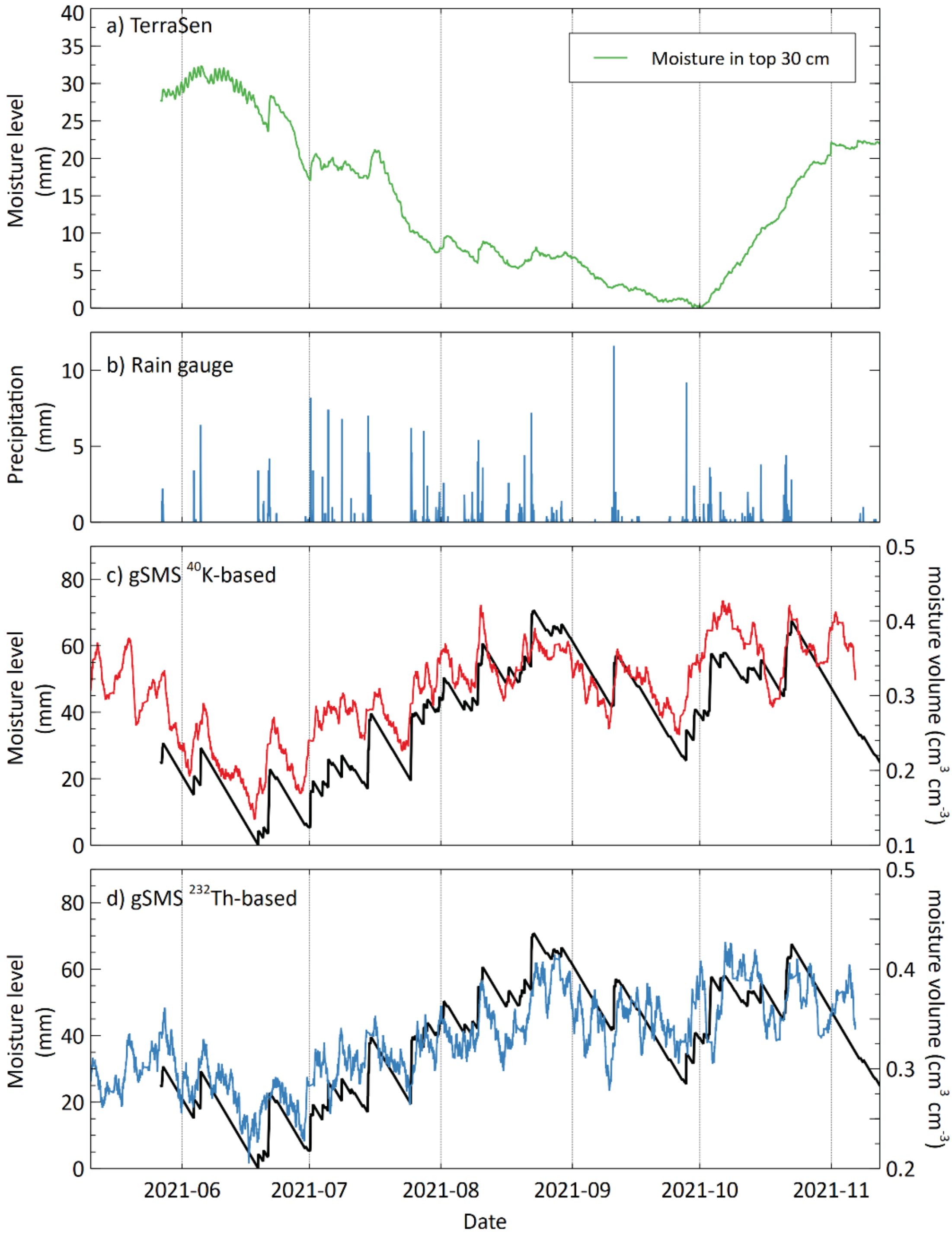

Fig. 6.11. a) Soil moisture content in the top 30 cm of the soil, derived from the top three sensors of the TerraSen and b) rain gauge readings in the period of the measurement campaign. The two bottom plots show the volumetric soil moisture content (right axis) calculated from the ^{40}K in c) and ^{232}Th concentrations in d) (red and dark blue lines). These bottom two plots contain a black line representing the moisture content (left axis) in the soil calculated by equation (6.5) and the rain gauge data. Note that the TerraSen in a) measures the moisture in a volume of three sensors = 0.042 m^3, and the gSMS measures the signal from a volume of 79 m^3.

6.5 Discussion

In this study, the effect of soil moisture on the reduction of gamma-ray flux was investigated. Our model shows that a proportional relation between volumetric soil moisture content and gamma-ray flux is expected. The presented experiment indicates that volumetric soil moisture contents calculated based on the gamma-ray flux from ^{40}K and ^{232}Th correlate with moisture content calculated on the basis of rain gauge measurements of precipitation. No such correlation is found for the TerraSen moisture sensors.

6.5.1 Soil moisture model

For the determination of soil moisture by using gamma-rays, it is imperative to know the factors that influence the gamma-ray flux, besides soil moisture. The well-known interaction of gamma-rays with their environment allows the theoretical study of the environmental effects that affect the gamma-ray flux in stationary measurements. This study presents an exhaustive list of the effects that can significantly affect the gamma-ray flux in such measurements. The measured gamma-ray flux is determined by radionuclides present in the soil and by the footprint of the measurement. The (specific) density of the soil determines the relation between gamma-ray flux and soil moisture. Atmospheric density fluctuation due to changing pressure and temperature has a straightforward and correctable effect on the flux intensity and becomes only significant (> 1.3 % intensity reduction) at spectrometer placement heights above 2 m. It is found that soil composition and water vapour present in the atmosphere do not significantly affect the gamma-ray flux (< 1 % intensity reduction).

Atmospheric radon will increase the measured gamma-ray flux during and right after precipitation events, an effect that can be used to filter out these data points. Biomass influences the gamma-ray flux as a function of H_2O present in the organic matter, which was only studied theoretically in this research and not applied to the field experiment because the effect was estimated to result in, at maximum, a 5 % reduction in gamma-ray flux.

6.5.2 Field study

The field study used a model to translate the observed gamma-ray flux due to the ^{40}K and ^{232}Th concentrations in the soil to volumetric soil moisture content. A simplified precipitation based model of the amount of moisture stored in the soil correlates well with the soil moisture content derived from the gamma-ray flux (Fig. 6.11c and d). Even when making the crude assumption that the total precipitation during the experiment is equal to the amount of evaporation results in a good first-order estimate of the moisture stored in the soil. To further improve the measurement of moisture using the gSMS, future experiments should consider to include gravimetric and above- and under-ground biomass measurements throughout the measurement campaign, such as done by Baldoncini et al. (2019). In a future study, the concentration directly before and after harvesting should be recorded and compared to quantify the effect of biomass on the gamma-ray signal. The yield of the harvest and an estimate of amount of biomass that remains in the field can be used to estimate the amount of moisture that was stored as biomass right before removing the crops from the field.

The proportional relationship between the gamma-ray flux and soil moisture concentration observed in our measurements is in line with the results observed by Baldoncini et al. (2019). Our research adds to this the prediction that there is no significant influence of the mineralogical composition of the soil, making it easier to apply these moisture measurements when this soil information is not available. Secondly, this is the first time the apparent ^{232}Th concentration is presented as a predictor of the volumetric soil moisture content. And thirdly, this research shows that a much smaller gamma-ray spectrometer can yield similar results, significantly impacting the affordability of such a sensor. Furthermore, the model presented here uses a physics based approach that incorporates a minimum of site-specific assumptions, such as local soil composition, which paves the path for the application outside the agricultural sector.

In our experiment, it is found that a precipitation event always corresponds with an increase in soil moisture content. However, not all increases in soil moisture correspond with a precipitation event. Fig. 6.11 (a, c and d) show a number of events where the soil moisture content increased without a precipitation event. The difference in our findings may be caused by an increase in soil moisture that is not registered by the rain gauge. This could be effects such as dew or drizzle rain at a rate lower than the measurement threshold of the rain gauge. Furthermore, it is found that the ^{232}Th based soil moisture estimations show more variation than those based on the ^{40}K concentration. This might be attributed to the different size of the footprint as a result of the different average energies used to derive the concentrations of both radionuclides. With the model presented in this research and the FSA method to derive the radionuclide concentrations in the experiment, it is not possible to attribute the origin of the differences in ^{40}K and ^{232}Th derived soil moisture content.

Both the TerraSen moisture measurements (Fig. 6.11a) and the gSMS derived moisture contents (Fig. 6.11c and d) show an increase in soil moisture in response to rain events. However, the large-scale structure of the measurements during the period of the experiment shows a completely different pattern. This mismatch could be caused by the inherent differences between the two sensors. The TerraSen provides a point measurement and reports the moisture level in the soil as a result of FDR measurements. The gamma sensor measures the radiation coming from within a larger volume (79 m^3). Another effect that could cause different readings is that no correction for biomass has been applied to the gSMS derived moisture percentages. But this effect is estimated to be at a maximum of 2.2 % in moisture level and cannot explain the large differences shown in Fig. 6.11. It is concluded that the two sensors measure a significantly different quantity: point measurement vs volumetric measurement, which means that both readings can be a representation of the true value of their respective parameters. However, the gSMS radionuclide data has a better correlation with the rain gauge based soil moisture model indicating a promising use for macro-scale moisture monitoring.

6.5.3 gSMS vs CRNS

The gamma-ray flux measurements have many similarities with the CRNS measurements (Stevanato et al., 2019; Zreda et al., 2012). Both techniques derive soil moisture from nuclear processes that cause the attenuation of either gamma-rays or neutrons. Because of the similarities in measurement principles, best practices from the more developed CRNS method may be transferred to the gamma-ray measurements. However, there are some significant differences between the techniques that make them complementary: the diameter of the area that contributes to the measurements is tens of meters for the gamma-ray measurements, whereas the CRNS method has a scale of hundreds of meters. But there are differences between the CRNS and the gSMS methods that may result in choosing one sensor over the other for a specific application. The count rate for gamma-ray measurements is less influenced by atmospheric variations or changes in the flux of cosmic rays (less correction needed) and is several magnitudes higher (higher accuracy). On the other hand, gSMS readings are influenced by the radon that is pushed down during rain events, which makes the CRNS preferable in areas with long lasting rain events.

6.6 Conclusions

The model developed in this research has shown that the mineralogical soil composition does not influence the gamma-ray flux. The mass attenuation coefficients for all elements found in significant quantities have a comparable value in the 0.3–3 MeV energy range, the range in which naturally occurring radionuclides emit gamma-ray photons. The gamma-ray flux intensity is only dependent on the (specific) soil density. For precision farming applications, the goal is to measure the moisture in the soil. Additional corrections have to be applied to achieve this goal with gamma-ray flux measurements: biomass corrections and a field calibration has to take place to derive the density of the soil. If these parameters are accounted for, it is possible to measure the absolute moisture in the soil.

Alternatively, the independence of surrounding material makes this technique transferrable to general environmental moisture measurements. The gamma-flux measurements can be used outside agricultural applications. For example, forestry applications that aim to monitor the amount of moisture in growing forests or the change in moisture stored in the canopy of the forest throughout seasons. Landscape management studies can use the gSMS to monitor changes in the moisture stored in the environment (groundwater + biomass) or the amount of snow present in an area. These gamma soil moisture measurements, in a soil volume between 4.1 and 186 m^3 in the 0.5–3 m sensor heigh range, can fill the gap in moisture measurements between point sensors (volume 0.014 m^3), such as the TDR and FDR measurements or rain gauges, and techniques that have a footprint up to tens of hectares, such as the CRNS method or satellite-based measurements (volume up to $7.0 * 10^5$ m^3).

Compared to the CRNS measurements, the gamma-ray flux technique may provide a more accurate approach to measure relatively rapid soil moisture changes due to its higher counting rate. Therefore, it is concluded that stationary gamma-ray flux measurements provide a way to measure changes in the quantity of H_2O present in the environment around the sensor. This is a new technique that has the potential to be used in precision agricultural, forestry or landscape management studies. The main topics for further research on this technique are the effect of biomass for a variety of agricultural crops and forests. This research can build forward on the work done on biomass estimation in a tomato field by Baldoncini et al. (2019). Secondly, future work should focus on a model that translates the gamma-ray flux measurements to absolute moisture levels in an area.

The main research question of this thesis is how to measure the absolute radionuclide concentrations in UAV-borne radiometric measurements. This chapter focussed on using gamma-ray spectrometers to determine the moisture content in the soil, a new application of gamma-ray spectrometers that can potentially be used in water management studies. However, the same procedures described in this chapter to go from gamma-ray flux to soil moisture can be reversed to correct for soil moisture. Consequently, in UAV-borne gamma-ray studies that map the radionuclide concentration in an area, the measured radionuclide concentrations can be corrected for soil moisture when this parameter is known or estimated.