Requirements and challenges in the measurement of soil moisture

Memo

Prepared by
Teknologisk Institut
Kongsvang Allé 29
8000 Aarhus C
Installation and Calibration

December 2022
Author: Emil Andreasen Klahn. Co-reader: Henrik Kjeldsen

DANISH
TECHNOLOGICAL
INSTITUTE

Contents

1. Purpose

Many soil processes benefit from an increased knowledge of the moisture that is present in soils. Assuring a correct level of irrigation is crucial in farming, as both under- and overirrigation leads to less-than-optimal crop yields, and overirrigation results in soil saturation and anaerobic conditions as well as wastes precious fresh water. The increased weather volatility that follows from a changing climate also mandates that soil moisture content should be monitored closely to be able to better predict water drainage after severe rain events. As such, soil moisture is one of several essential climate variables (ECVs) defined by the Global Climate Observing System (GCOS) under the World Meteorological Organization (WMO) [1]. Techniques for measuring soil moisture range from point-scale sensors that measure on a length scale of centimeters, typically through measuring the electric properties of soil, to measurements by neutron scattering that relate the energy loss of emitted neutrons to the water content in soil, and by satellites measuring microwaves reflected or emitted by Earth's surface.

These sensing techniques are commonly calibrated against the thermogravimetric technique, or loss-on-drying (LoD), that measures moisture content by measuring the mass of a sample of material before and after drying in an oven according to a specified procedure [2]. A known issue with this method is, however, that unknown amounts of volatile compounds (VCs) may evaporate during the drying process, which increases the uncertainty and compromises the metrological traceability of the LoD-method.

Dedicated equipment and procedures for traceable calibration of soil moisture sensors can mediate these issues. This memo thus describes challenges and requirements in the measurement of soil moisture using the primary standard for water content measurements at the material moisture laboratory of the Section for Metrology (MET), Center for Installation and Calibration at the Danish Technological Institute (DTI). Furthermore, it describes our initial thoughts about the expected requirements for developing a calibration procedure for point-scale soil moisture sensors in that regard.

2. DTI primary standard for material moisture

The material moisture lab at DTI uses a primary standard for measuring water content of materials that will be adapted to work with soil samples. The setup is based on the evolved water vapor (EWV) principle and it measures the water content of a dry transport gas (N_2) after it has passed a heated sample by determining the dew point of the humid gas. Traceability to the SI system is ensured through a documented measurement procedure and by enforcing traceable calibrations of each of the sensors in the setup [3].

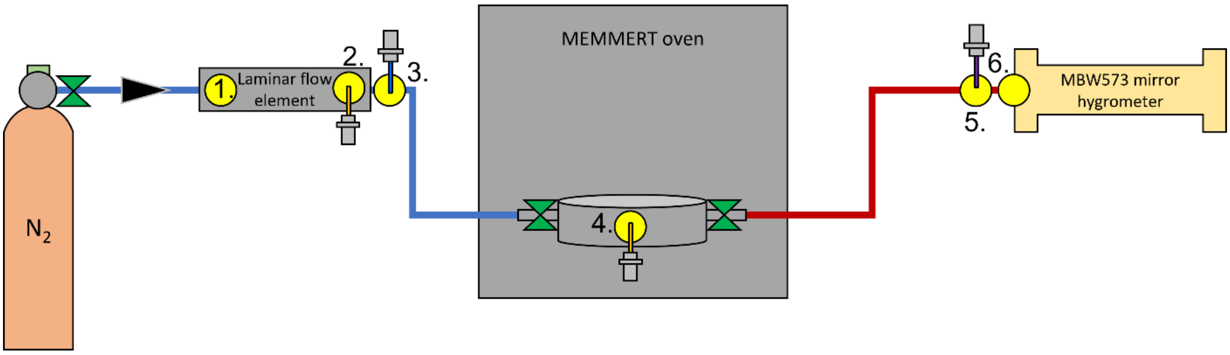


Figure 1 Schematic drawing of the reference setup at DTI. Yellow circles represent points where a measurement of any sort is taken. Blue and red lines represent transport lines of cold (dry) and hot (wet) gas respectively.

By accumulating the measurements of amount of water evaporated from the sample during the drying process, and by measuring the mass of the dry sample, the water mass fraction, $\mathcal{W}$ is determined as

$$\mathcal{W} = \frac{m_w}{m_d}$$

where m_w is the mass of the evaporated water and m_d is the dry mass of the soil [2]. Similarly, a volumetric water content, θ, of a sample is given by the water volume fraction and is obtained by

$$\theta = \frac{V_w}{V_d} = \frac{\gamma_d}{\gamma_w} \cdot \mathcal{W}$$

where V_w and V_d are the volumes of water and dry sample respectively, γ is the bulk density, where γ_d is the bulk density of the dry soil, i.e. the weight that a volume of dry soil has per unit volume of that soil when it had water in it. It is thus necessary to know these values to determine the volumetric water content from the measurements with the DTI primary standard. Importantly, these quantities are not the same as the mass and volumetric *moisture* content, as the primary standard measures the total evaporable water in a sample and only that. Other moisture contributions stemming from for example organic matter are not measured by this setup.

2.1. Measurement points

The following quantities are measured at the points marked with yellow circles in Figure 1. Together, 1, 2, and 3 measure the gas flow

1) Laminar flow element that measures pressure difference across the flow to determine the gas flow. The flow of the dry gas is controlled to be roughly 1 L/min.
2) Pressure sensor to determine absolute pressure in the system. This is not markedly different from atmospheric pressure.

3) Temperature sensor to determine temperature of the dry transport gas. The transport gas is kept at room temperature.
4) Temperature sensor to determine sample temperature. This varies from room temperature and never goes above the maximum setpoint of the oven at 105 °C.
5) Thermohygrometer to determine dew point.
6) Mirror hygrometer to determine dew point. For this value (and the value measured under point 5), the setup operates at approximately 50 °C.

3. Challenges for operating the primary standard

The setup and working documentation of the primary standard of materials has been published previously [3]. Therefore, the challenge in working with soil samples lies in validating the setup for soil samples, as well as developing procedures to handle soil samples and to protect the setup from contamination effects that come with measuring soil.

3.1. Mirror maintenance

Sensing of humidity with a mirror hygrometer can give uncertainties of less than 0.1 °C in the dew point of the wet gas, corresponding to an uncertainty in the absolute humidity of around 0.1 mg/L. However, the mirror is highly sensitive to contamination by volatile compounds evaporating from the soil samples that condensate on the mirror. Regular cleaning is thus necessary to ensure optimal working conditions for the mirror [4].
This causes a particular challenge when measuring soil. Soil inherently contains contaminants, such as very small dust particles and volatile compounds from either plant residuals or microbial activity, which can be moved along with the transport gas and settle on the mirror and add uncertainty to the dew point as determined by the mirror hygrometer.

This challenge is mediated by filtering the wet gas. Currently, an air filter is installed at the inlet of the hot transport line (see Figure 1 for reference), and the installation of other filters could also be considered. It has been observed in the measurement of moisture in wood chips, however, that very small particles still pass by the filter, such that hoses further down the line are affected by contamination. Further mediation of this challenge could be to circumvent the mirror hygrometer in most measurements and instead measure the water content of the wet gas with a thermohygrometer such as the Vaisala HMP9, with the added benefit that the mirror could be reserved for a periodic calibration of this sensor.

3.2. Sample chamber cleaning

The sample chamber, located between the cold and hot line in Figure 1, consist of a metal container, which can be sealed with valves when it is not used as a part of the setup. This ensures that the moisture content of the sample does not change once it has been sealed in the chamber. Currently, the chamber requires cleaning after each measurement, as the sample is placed directly in a built-in sieve in the chamber. The path of the transport gas, which is let into the chamber at the bottom and out at the top, thus goes through the sample.

Figure 2 Left: Sample chamber installed in the oven of the primary standard. The gas inlet is installed in the bottom of the chamber on the left, and the outlet is installed in the top of the chamber on the right. Right: View of the open sample chamber with wood chips placed on top of the built-in sieve.

The measurement does not necessitate that the path of the transport gas goes through the sample. A removable sample holder in the sample chamber could therefore increase the ease-of-use of the setup as a sample could easily be removed and discarded from the sample chamber. This challenge has not been addressed earlier, as for example the relatively homogenous nature of a sample like wood chips makes them easy to remove from the sample chamber, compared to the heterogeneous nature of soil.

4. Challenges and requirements for a calibration procedure

Traceable calibration of a sensor means that the measurements of an uncalibrated sensor are compared to the measurements of a calibrated sensor with proper accounting of the measurement uncertainties and traceability to the SI-system. One area where such a calibration will be required for soil moisture sensors is in task 1.2 of the project *Metrology for multi-scale monitoring of soil moisture* (SoMMet), funded by the European Partnership on Metrology (EPM), which will develop calibration procedures for point scale sensors of soil moisture. The process outlined below shows what is thought to be the steps in performing such a calibration with the DTI primary standard in order to facilitate a discussion about the individual steps.

1. Point sensor and soil samples of a specific soil are sent to the calibration laboratory
2. Make measurements with point sensor
3. Make measurements with reference setup
4. Compare the measurements from point sensor and reference setup

4.1. Soil type, possibility of reuse and sample transport

Soil comes in many different types [5]. Different soils have different values of descriptors such as the balance between inorganic and organic contents of the soil, soil texture, soil structure, water content capacity, and bulk density (affected for example by time since last disturbance) [6]. This is why emphasis must be put on collecting samples of a *specific* soil for which a given soil moisture sensor will be used. As an example, soil moisture sensors working on the principle of electrical conductance will be affected by soil salt content and inhomogeneity. Calibrations of soil moisture sensors are thus not universal across soil types.

The DTI primary standard measures the content of water in the soil sample used for giving a calibration reading with a sensor. The water is extracted by heat and is detected by measuring the dew point of the transport gas N_2. The heat treatment of the soil means that this measurement is destructive. While other moisture, such as organic compounds that evaporate, are not measured by the primary standard, they are affected by the heat treatment, and the composition is therefore different before and after measurement. The degree to which the sample is affected again depends on soil type, as soils with a high degree of inorganic content will be more resilient to heat treatment and cooling. Even for these samples, however, possible soil structure can change properties after heating.

Thus, another thing to consider is the effect of the heat profile applied to the sample by the measurement setup. As shown by Bell et al. [7], more water can be driven off a sample the more the sample is heated. Heating in three steps of 50 °C, 80 °C, and 150 °C, the authors show, by measuring electrolytic current, that more water can be released every time the temperature is increased. The heat profile of the measurement, the amount of water driven off the sample by a particular heat profile, and the destructive effect of heat on a specific soil type should therefore be considered when designing calibration procedures.

The change in soil composition upon heating is important when considering whether soils can be reused for calibration purposes. Ideally, water can be reintroduced to a soil sample so that an unknown sensor can be calibrated over a wide range of soil water contents, and the feasibility of this approach should be addressed when establishing calibration facilities for soil moisture sensors.

Finally, it is important to consider soil sample transportation and storage. The water content of a soil sample will inadvertently change between the time of taking soil sample and the time of measurement with the reference setup, and the degree of changes will depend on storage time and the storage conditions of the sample.

Because the water content changes, the calibration procedure will also have to consider the transportation and storage conditions for soil samples. We consider two situations. In one case, the measurement with the point scale sensor is performed in the field before the sample is picked up and transported to be measured at the reference setup. This will give the sensor reading that most closely resembles field conditions. However, the amount of soil that contributes to the signal in the point scale sensor needs to be known so all of it can be collected and measured, and this would clearly be infeasible for long sensors such as that shown in Figure 4. Furthermore, the soil water content will change during transportation, and the uncertainty contribution from that should be addressed. In another case, a sample could be picked and transported to the reference setup, and a reading is then taken with the point scale sensor immediately before measuring the water content of the sample in the reference setup. In this case, the soil density may change due to the sample being removed from the field environment, which also contributes to the uncertainty in relation to field conditions.

To address how the sample transportation changes the water content, DTI is working on establishing how different sample transport bags retain moisture in a sample. These bags are for example zip-lock plastic bags and aluminium bags. As an example, the DTI division AgroTech uses commercially available zip-lock plastic bags for store and transport. Experience suggests that the moisture content in a soil sample stored in such bags and cooled with ice boxes (to keep the samples around 2 to 4 degree centigrade) stays constant for up to 48 hours. Sample transportation and storage for soil samples for the calibration procedure will also look towards the standards described in ISO 18400-105:2007 (Soil quality – sampling – Part 105: Packaging, transport, storage, and preservation of samples) and ISO 18512:2007 (Soil quality – Guidance on long and short term storage of soil samples) for guidance.

The challenge of designing a sample chamber that is good for sample transport and storage as well as for use in a calibration will be addressed in the following section.

4.2. Practical considerations for soil moisture sensor calibration

The soil moisture content is expected to change slightly every time a sample is handled. Therefore, a requirement of the calibration procedure is that sample handling is minimized. This, in turn, requires that the sample is stored and transported in a way that minimizes sample handling.

In SoMMet work package 1 (WP1), calibration procedures for point scale sensors, such as the one shown in Figure 4, will be developed. The device has 6 pairs of electrodes on the length of the sensor, and a soil moisture reading will be produced for each pair of electrodes. The stick is inserted in the soil by first inserting a tube in the soil and next inserting the sensor stick in the tube. Other sensors work by inserting a metal rod in the soil and give one reading.

The primary standard measures all water content and compares that to the mass of the dry sample, giving the average water content, while sensors may be influenced by local inhomogeneities within the individual soil sample. In the case that of high moisture content coexist with of low moisture content within a soil sample, a local reading with the uncalibrated sensor is likely to give an unrepresentative reading of the average moisture content of the sample. The risk of this occurring will depend on soil type, as the dynamics of water transport within a sample is soil type dependent. The inhomogeneity of a soil sample should therefore be addressed in the calibration procedure. As an example, the DTI calibration procedure for wood moisture meters requires several measurements of the same wood sample during a calibration to control for the inhomogeneity of the sample. A similar requirement should be possible to enforce in the calibration of soil moisture sensors. One suggestion for a sample chamber allowing for multiple readings is shown in Figure 3. There are several openings in the sample chamber that can each be sealed with a lid. While these openings would be shut during the measurement in the primary standard, where only one line in and out of the chamber exists, each opening give the possibility of a separate measurement with a soil moisture sensor. This gives the possibility of evaluating the homogeneity of the soil sample through multiple measurements at different positions throughout the same volume of soil. As a more elaborate mechanism for controlling moisture retention, a perforated rubber membrane could be fitted in the opening, such that the opening remains somewhat sealed while there is no sensor in the opening.

Figure 3 also includes a suggestion for calibrating the long stick sensor shown in Figure 4. Instead of having multiple different sample chambers, the sample chamber can allow the stick to pass through the soil sample, such that the same reading would be expected for each sensor on the stick.

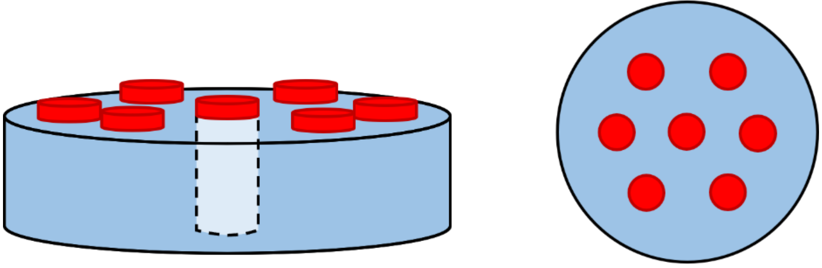
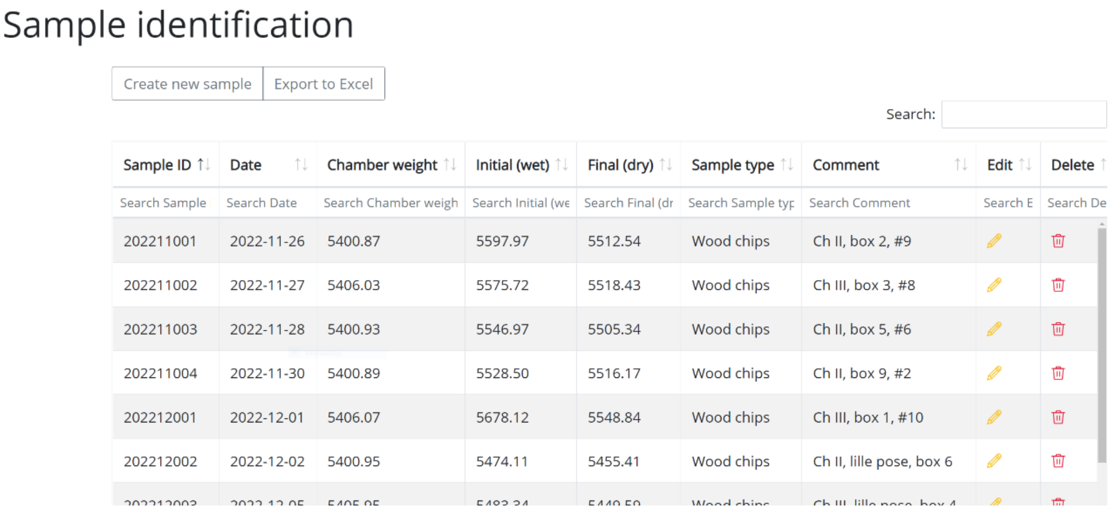


Figure 3 Suggestion of a sample chamber allowing for readings at different positions in the soil sample. The middle opening sketches a possibility for calibrating the soil moisture sensor shown in Figure 4.

Figure 4 Soil moisture sensor that produces moisture readings at different depths at the same time.

The fact that soil samples will be collected, transported, and measured in the DTI primary standard mandates the establishment of a common standard for naming and tracking soil samples. DTI is working towards providing this functionality with a common web interface through the DTI system YoDa that can be accessed from any web-browser. A screenshot of a prototype app is shown in Figure 5, and each sample can contain several more points of metadata, such as the sampling site, sensor type (if a measurement has been made with a point-scale sensor), and sensor readings of the same sample.



Sample identification

Sample ID	Date	Chamber weight	Initial (wet)	Final (dry)	Sample type	Comment	Edit	Delete
Search Sample	Search Date	Search Chamber weigh	Search Initial (we	Search Final (dr	Search Sample typ	Search Comment	Search E	Search De
202211001	2022-11-26	5400.87	5597.97	5512.54	Wood chips	Ch II, box 2, #9	✎	🗑
202211002	2022-11-27	5406.03	5575.72	5518.43	Wood chips	Ch III, box 3, #8	✎	🗑
202211003	2022-11-28	5400.93	5546.97	5505.34	Wood chips	Ch II, box 5, #6	✎	🗑
202211004	2022-11-30	5400.89	5528.50	5516.17	Wood chips	Ch II, box 9, #2	✎	🗑
202212001	2022-12-01	5406.07	5678.12	5548.84	Wood chips	Ch III, box 1, #10	✎	🗑
202212002	2022-12-02	5400.95	5474.11	5455.41	Wood chips	Ch II, lille pose, box 6	✎	🗑

Figure 5 Prototype app for sharing sample identification numbers and comments about sample handling across the project partners involved in gathering and measuring soil samples.

5. Conclusion

In this memo, initial thoughts, and remarks regarding the establishment of a calibration procedure for soil moisture sensors in the SoMMet-project have been presented. We describe the DTI primary reference method for moisture content measurements, and we describe the practical challenges in measuring soil moisture with that standard. That relates to cleaning dust off the mirror in the mirror hygrometer, possible contamination of volatile compounds, cleaning the sample chamber, and minimum handling procedure. It is suggested that the mirror hygrometer is circumvented for most measurements to avoid contamination, and that an insert is installed in the sample chamber that can easily be removed and cleaned.

For developing a calibration procedure, it is necessary to consider the nature of the soil being measured and the water retention during transport. A challenge to be addressed later is whether soil moisture content can reliably be retained during transport, and what transport containers are best suited for that purpose. Finally, the homogeneity of the moisture content must be controlled for, meaning that the sample chamber must allow for multiple readings on the same sample. This puts constraints on the design of the sample chamber, a suggestion for which has been shown here to be revisited in WP1 of the SoMMet project.

6. Acknowledgements

This study was supported by a grant from Danish Technological Institutes performance contract 2021-2024, entered with the Danish Agency for Higher Education and Science, under The Ministry of Higher Education and Science Denmark. Collaborators are greatly acknowledged. The project 21GRD08 SoMMet has received funding from the European Partnership on Metrology, co-financed by the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Co-funded by the European Union
European Partnership
METROLOGY PARTNERSHIP
EURAMET

7. References

[1] GCOS, "Soil Moisture - Essential Climate Variable Fact Sheet." https://ane4bf-datap1.s3.eu-west-1.amazonaws.com/wmod8_climatedata/s3fs-public/soil_moisture_ecv_factsheet_201905.pdf?MUnJZ_2ZD9rTzk593vbxodKPpN_HTsOt

[2] F. Sanna, *Soil moisture measurements and calibration methods*, 1st editio. Beau Bassin: Scholars Press, 2018.

[3] P. Østergaard and J. Nielsen, "SI-Traceable Water Content Measurements in Solids, Bulks, and Powders," *Int. J. Thermophys.*, vol. 39, no. 1, pp. 1–13, Jan. 2018, doi: 10.1007/S10765-017-2325-4/TABLES/3.

[4] "Dew Point Mirror 573 Operating and maintenance manual." https://www.mbw.ch/wp-content/uploads/2015/02/MBW573_Manual_E_V3.1.pdf (accessed Dec. 15, 2022).

[5] Soil Service Staff, *Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys*, 2nd editio. US Department of Agriculture, 1999.

[6] C. Hignett and S. Evett, "Direct and Surrogate Measures of Soil Water Content," in *Field Estimation of Soil Water Content*, Vienna: International Atomic Energy Agency, 2008.

[7] S. A. Bell, P. Miao, and P. A. Carroll, "Novel Calibration Technique for a Coulometric Evolved Vapor Analyzer for Measuring Water Content of Materials," *Int. J. Thermophys.*, vol. 39, no. 4, pp. 1–13, Apr. 2018, doi: 10.1007/S10765-018-2368-1/TABLES/2.

DANISH
TECHNOLOGICAL
INSTITUTE