21GRD08 SoMMet

# Publishable Summary for 21GRD08 SoMMet
# Metrology for multi-scale monitoring of soil moisture

## Overview

Water and soil are vital resources that are seriously affected by climate change and degradation. Water at the land surface, primarily in the form of soil moisture, is a key resource influencing agriculture, forestry, groundwater recharge, weather, climate, and greenhouse gas emissions. Several soil moisture observation systems exist on multiple scales, but they need to be harmonised. The overall objective of this project is to develop novel metrological tools and establish a metrological foundation for soil moisture measurements on multiple lateral scales, ranging from decimetre to kilometre, ensuring the traceability and harmonisation of the various soil moisture measurement methods.

## Need

Soil moisture is one of the Essential Climate Variables (ECVs) as defined by the Global Climate Observing System (GCOS) of the World Meteorological Organisation (WMO). Soil moisture influences the land-atmosphere interactions on both weather and climate timescales. Long-term carbon storage and release in soil is strongly influenced by soil moisture - only a healthy and adequately moist soil can act as carbon sink in the strategies for greenhouse gases reduction and adaptation to climate change impacts. Soils are a cross-cutting theme within the European Green Deal (EGD), communicated by the European Commission in 'EC COM/2019/640 final', as the sectors of water management, agriculture, forestry, and biodiversity are inherently interdependent.

Soil moisture measurements at point scales, performed by practical users in agriculture and hydrology or by scientists dealing with soil moisture as an ECV, are not representative of the soil moisture at the larger scales that are relevant for practical applications. Point scale measurements use physical tactile sensors which are invasive and subject to local issues. To overcome this, complex sampling designs and interpolation methods can be implemented, however uncertainties need to be improved and practical calibration guidelines developed. Remote observation of the Earth can be used for real-time and continuous assessment of soil moisture on the kilometre-scale however intermediate scale soil moisture methods such as cosmic-ray neutron sensing (CRNS) are needed so that gap from point scale to remote sensing can be bridged. The CRNS methodology needs to be harmonised and reliable calibration, validation and characterisation methods developed.

There is an overall need for comparison and harmonisation of soil moisture observations at different spatial and temporal scales based on different methods. Furthermore, 'the next logical step' is needed, i.e., performing the data fusion of the multi-scale soil moisture measurements to generate high-quality, temporally, and spatially consistent soil moisture information, useful for land surface sciences and applications, such as climate observations, weather forecasting, hydrology, and agriculture.

## Objectives

The overall aim of this project is to develop novel and traceable methods and establish a metrological infrastructure for soil moisture measurements covering lateral scales ranging from the decimetre to kilometre.

The specific objectives of the project are:

**Report Status:**
**PU –** Public, fully open

**Publishable Summary**

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1. To develop metrological framework, including primary and secondary transfer standards, to ensure SI-traceable point-scale soil moisture measurements with uncertainties of 5 % under laboratory conditions. To develop metrological framework for validation of existing cosmic-ray neutron sensing (CRNS) devices, currently available in the market, under laboratory conditions.
2. To develop new validation practices for cosmic-ray neutron sensing (CRNS) methodology for use in outdoor conditions. This includes the application and validation of neutron transport models used to interpret CRNS detector signals specific to the soil moisture measurand, and the standardisation of the CRNS on-field calibration procedure for soil moisture assessment on lateral scales ranging from $10^2$ m to $10^3$ m and to depths of up to 1 metre.
3. To investigate the constraints and accuracy of soil moisture measurement methodologies using intercomparison campaigns on local and remote sensing. In addition, to develop procedures, summarized in good practice guides, to overcome (i) temporal and spatial differences regarding the sensing domains of soil moisture measurement methods and (ii) the influence of other state variables such as air humidity and soil temperature affecting the measurements.
4. To develop a multi-scale metrological system and metrologically traceable methods for soil moisture monitoring, covering lateral scales ranging from $10^{-1}$ m to $10^3$ m and to depths of up to 1 metre and temporal scales ranging from hours to days, to assess the soil moisture with traceable relative uncertainty of 20 % or better. This includes the development of a cross-disciplinary harmonisation system on the medium sub-kilometre-scale and the establishment of (i) metrological traceability of soil moisture measurements using point-scale sensors (from Objective 1) and satellite measurement techniques and (ii) fit for purpose modelling. In addition, to develop techniques to support the harmonisation of soil moisture assessment.
5. To cooperate with user communities to define design criteria for emerging and future hydrological and meteorological/climatological soil moisture networks using the combination of point-, intermediate- and large-scale methods. To cooperate with the European Metrology Network for Climate and Ocean Observation (EMN COO) and relevant international organisations (e.g., WMO) to facilitate the dissemination of the project outputs.

**Progress beyond the state of the art and results**

Several soil moisture observation systems have been developed, ranging from invasive point-scale soil moisture sensors to large-scale remote sensing products. In addition, more recently, a non-invasive intermediate scale soil moisture method, cosmic-ray neutron sensing (CRNS) has found widespread use. Despite several initiatives, no harmonisation approaches under metrology standards are available. This project will address this gap by developing the metrological tools needed for traceable and validated soil moisture measurements. For the first time, metrological tools for all three domains/scales will be considered in a holistic approach, to harmonise soil moisture monitoring across scales.

*Metrologically traceable methods for multi-scale soil moisture measurements:* New traceable methods for the measurement of soil moisture in outdoor conditions on lateral scales in the range of $10^{-1}$ m to $10^3$ m with relative combined uncertainty of 20 % will be developed. To achieve this, new standards and methods for the traceability of the point-scale soil moisture measurements under laboratory conditions are under development (at the facilities of project participants DTI, TUBITAK and CMI). Later, the measurement supply chain will be extended to outdoor conditions by transfer standards and an improved on-field sampling method. The calibration procedures for point-scale sensors, as they are being used in different communities, have been reviewed from the SI-traceability perspective. The SI-traceability scheme has been set out for the measurement of moisture in soil samples under laboratory conditions. The primary reference setup of DTI, which was previously developed in the framework of the EMRP project SIB64 METefnet for determination of moisture in solid samples, but not in soil samples, was adapted specifically for soil moisture measurements. The setup is now being commissioned and validated in laboratory with various soil samples. The transfer (secondary) standard, based on loss on drying (LoD) method, has been designed and is currently under construction. An interlaboratory comparison of the different reference methods is planned. The primary and secondary reference setups will make it possible to carry out the SI-traceability chain from the laboratories to the outdoor conditions.

*New traceability scheme and validation practices for CRNS method:* A traceability scheme for CRNS methodology is currently under development. The validation of the CRNS systems models and their neutron response functions is currently in progress, using computing cluster-aided calculations and dedicated measurement campaigns in neutron reference fields. The existing facilities of the neutron metrology community have been reviewed from the perspective of usability for the specific needs of the SI-traceable validation and characterisation of the instruments used in the CRNS methodology. The state-of-the-art CRNS instruments, currently available on the market which are being used in existing and emerging CRNS networks, have been reviewed and three different types of CRNS devices were selected to be characterized and investigated in the project in detail. The CRNS devices are modelled using suitable Monte Carlo-based radiation transport codes. The SI-traceable measurement of neutrons in the neutron metrology laboratories makes it possible to validate these models. In the next step, the neutron response functions will be calculated based on the validated models. This will allow for an effective validation of current and upcoming CRNS system designs. The combination of metrology for neutron radiation and metrology of temperature and humidity will allow, for the first time, a traceable benchmarking of CRNS devices under outdoor conditions, leading to new validation practices. There will be improved understanding of the CRNS footprint (sensing volume), of systematic effects, and of the uncertainty of the soil moisture retrieval.

*New on-field comparison campaigns on local and remote sensing:* New soil moisture data are systematically collected at established experimental field sites, operated by participants, and selected according to their relevance for the calibration and validation practices of soil moisture retrieval by CRNS and remote sensing. This data will be a clear improvement over previous historical data sets as they will be based on newly characterised devices of point-scale and CRNS methods, and the measurements will be designed for the purpose of harmonisation. The data will be used to investigate the limitations and accuracy of the individual methods. New approaches and methods will be developed to overcome the temporal and spatial differences regarding the sensing domains of the individual methods. Three high-level test field sites and two accompanying sites were selected. On the high-level test field site, systematic data taking is being planned with the three soil moisture measurement methods, namely with the point-scale sensors, the CRNS instruments, and the satellite-based remote sensing. A unified data retrieval and data processing system is in operation, enabling an automatic processing and feeding of the field data into the project's data storage and management system. The actual measurement campaigns of systematic soil moisture measurement on all three high-level test field sites are currently in preparation.

*Cross-disciplinary harmonisation system for soil moisture monitoring:* Based on the newly collected data sets, and on the historical time series, novel procedures for harmonising soil moisture assessments on different temporal scales and on lateral scales ranging from point scale to kilometre scale will be developed. New recommendations for the calibration and validation practices of the soil moisture retrieval by remote sensing, as well as new methodologies for data fusion, will be developed. Extensive literature studies were carried out to review and categorize the existing methods to characterize spatial and temporal soil moisture observations, the existing soil moisture harmonisation methods, as well as the state-of-the-art data fusion methods for soil moisture estimation at different spatiotemporal scales. The input from the project's Stakeholder Committee was received as well. This gathered knowledge is now the starting point for the activities that will build upon the new soil moisture data collected within the project.

**Outcomes and impact**

The project created a Stakeholder Committee (SC) consisting of soil moisture experts from various communities, including representatives of the European Space Agency, the experts leadingly involved in the International Soil Moisture Network, the Land Product Validation Subgroup of the Working Group on Calibration and Validation of the Committee on Earth Observation Satellites, experts on soil moisture products from remote sensing and experts on hydrology, soil physics and (agro)meteorology. The SC grows further as the consortium promotes the project to communities such as manufacturers of the meteorological equipment. A valuable input was obtained from the SC on the needs for metrology support of the various interested parties. Links to other projects, networks and national meteorology services dealing with soil moisture assessment have been established. The consortium participated in several conferences to promote the project and has engaged with experts from the relevant communities. A stakeholder survey was carried out and valuable feedback was obtained. Furthermore, an information exchange meeting was held on metrology principles and open issues of soil moisture measurement on multiple scales. This event improved the understanding between metrology and non-metrology communities and increased the awareness of the project.

*Outcomes for industrial and other user communities*

The calibration procedure developed in this project will allow manufacturers of hydro-meteorological equipment to certify the performance of their instruments based on standard procedures. Manufacturers of laboratory equipment for instrument calibration will benefit from the project outcomes as well, since they will be able to provide compliant calibration devices for soil moisture instruments. This will enable them to market standardised and interoperable equipment and services that will underpin the harmonisation efforts in application areas such as weather monitoring and forecasting, and precision farming.

The project directly liaises with industrial stakeholders via the Stakeholder Committee (SC). The SC includes representatives from agro-meteorological services, national meteorological services, WMO members of expert teams, regional instrument centres, manufacturers centres, and is helping the project's results to directly impact such representatives. Based on the stakeholder survey and with the help of the SC members, contacts to various manufacturers of the meteorological equipment have been established, especially to the manufacturers of soil moisture measurement equipment. Their needs for metrological support and sound metrological foundation have become part of the project inputs. The benefits of the upcoming project developments have been communicated to these communities, and the active information exchange with them will remain a key part of the project's dissemination and communication strategies.

*Outcomes for the metrology and scientific communities*

SI-traceable metrology for water content in materials has been partly established over the last decade. However, at present, no countries have BIPM Calibration and Measurement Capabilities for moisture measurement, and SI-traceable measurements of soil moisture on primary level have, to our knowledge, not been reported. One important outcome of this project is to establish primary-level soil moisture measurements with developed uncertainty budgets. The established metrological foundation for soil moisture measurement should allow traceable calibration and validation of secondary measurement standards such as those based on traditional loss-on-drying and of transfer standards.

For soil moisture measurement there are currently unresolved issues with appropriate transfer standards and sampling methods. This project will address these issues and the transfer of the metrological chain of traceability to outdoor conditions, using new transfer standards based on visible and near-infrared spectral reflectance measurements for on-site calibrations. This improved metrological basis will be used for improving the CRNS methodology and should have direct impact on networks in Europe and worldwide. Harmonised multi-scale soil moisture data, with reliable uncertainties, will improve hydrological modelling, climate and weather forecasting by ensuring better comparability between data sets obtained with different methods.

The project was promoted on four European-scale conferences of scientific communities dealing with hydrological observations as well as monitoring and SI-traceable measurement of ionising radiation in environment.

*Outcomes for relevant standards*

Currently, most of the guidance for soil moisture measurements in the field is contained in good practice guidelines, and there is a lack of relevant validation and standardisation. Standardised procedures based on suitable calibration devices would benefit manufacturers and users of soil moisture instruments. Indeed, their use is currently limited due to insufficient standardised calibration procedures and the lack of both metrological comparison and harmonisation among different sensor typologies and gravimetric/volumetric manual soil moisture measurements.

This project will support standardisation work for soil moisture measurements by providing a technical report to CEN TC444 Environmental Characterisation WG5 Physical tests for consideration and adoption as well as to ISO TC-190 Soil quality WG1 Soil and Climate Change SC3 Chemical and physical characterisation for update of an existing standard. The project will also provide input to WMO Standing Committee on Measurements, Instrumentation and Traceability (WMO SC-MINT), WMO Commission for Observation, Infrastructure and Information Systems (INFCOM), WMO Commission for Instruments and Methods of Observation (CIMO) expert team on Operational Metrology, WMO Global Climate Observing System (GCOS) Surface Reference Network, WMO SC-MINT expert team on Measurement Uncertainty (ET-MU), EURAMET Technical Committee for Thermometry (TC-T) and BIPM Consultative Committee for Thermometry Working Group for Humidity (CCT-WG-Hu). The goal of the project is also to provide input to guidance material such

as updates to the WMO 'Guide to Meteorological Instruments and Methods of Observation' (WMO Guide No. 8).

The project was promoted in various face-to-face meetings with metrology experts, in particular the project's consortium activities were presented to the plenary meetings of the EURAMET TC-T and the BIPM CCT-WG-Hu.

*Longer-term economic, social and environmental impacts*

A wider impact of the project results is expected on companies operating in the fields of hydro-meteorological warnings, water resources management, flood control, agriculture and hydro-power plants. These companies provide services based on the monitoring of hydro-meteorological variables and the processing of the related measurements to support the final users' decisions about the configuration of industrial systems, even in real time. The use of calibrated soil moisture type instruments, in conjunction with the other meteorological observables, would improve the management capabilities of the users since decisions would be based on traceable measurements. With more reliable data it would therefore be possible to promptly inform the weather services, local agro-meteorology consortia and users, about the risk of drought and flood. The accuracy of such information is vital for the issuing of effective and timely warnings. This main economic impact would therefore be two-fold; an increase in trustworthy and timelier irrigation plans, with direct benefits on agricultural and farming production and reduction of water waste for irrigation and hence increased water availability.

Based on a general lack of traceability and data quality in historical observation, the Global Climate Observing System (GCOS) is preparing the creation of the GCOS Surface Reference Network (GSRN). Among the Essential Climate Variables prescribed by GSRN, soil moisture is one of the fundamental observed quantities for a reference site. The non-contact systems developed in the project will offer more reliable data and are a good candidate for long-term data series recording. In addition, this project is expected to have a substantial impact in climate science through the GCOS and other similar initiatives.

## List of publications

Gianessi, S. et al. (2024) 'Testing a novel sensor design to jointly measure cosmic-ray neutrons, muons and gamma rays for non-invasive soil moisture estimation', Geosci. Instrum. Method. Data Syst., 13, 9-25, Available at https://doi.org/10.5194/gi-13-9-2024

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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| Project start date and duration: | | October 2022, 36 months |
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| Internal Beneficiaries:<br>1. PTB, Germany<br>2. CIEMAT, Spain<br>3. CMI, Czech Republic<br>4. DTI, Denmark<br>5. INRIM, Italy<br>6. IRSN, France<br>7. JV, Norway<br>8. SMU, Slovakia<br>9. TUBITAK, Türkiye | External Beneficiaries:<br>10. CNR, Italy<br>11. CTU, Czech Republic<br>12. IAPAN, Poland<br>13. PoliMi, Italy<br>14. UFZ, Germany<br>15. UHEI, Germany<br>16. UNIBO, Italy<br>17. UP DE, Germany | Unfunded Beneficiaries: |
| Associated Partners: 18. UKCEH, United Kingdom | | |