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 (GHG) reduction and adaptation to climate change impacts. Soils are a cross-cutting theme within the European Green Deal (EGD), communicated by the European Commission (EC) in 'EC COM/2019/640 final', as the sectors of water management, agriculture, forestry, and biodiversity are inherently interdependent. Soil quality and soil moisture play a key role in the future EGD policies, namely in the future Common Agricultural Policies unified under the Farm to Fork Strategy ('EC COM/2020/381 final'), policies for environmental protection (Biodiversity Strategy for 2030, 'EC COM/2020/380 final') and the climate change action (The European Climate Law, 'EC COM/2020/80 final').

Soil moisture measurements at point scales, performed by practical users in agriculture and hydrology (e.g., farmers, agronomists) or by scientists dealing with soil moisture as an ECV, are not immediately 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 necessary hardware and data processing tools need to be harmonised and reliable calibration, validation and characterisation methods developed. Several comparison campaigns of soil moisture measurement methods at different spatial and temporal scales have been performed however many research areas (e.g., for the remote sensing of surface temperature for meteorology and climatology) have recognised the need for the integration of observations at different spatial scales based on different methods. There is a need for new on-field comparison campaigns to provide researchers with datasets using traceable methods which can be used to review the existing approaches and develop novel methods to overcome the limitations and different estimates of the soil moisture measurand derived from existing methods. In addition, there is also a need to set out appropriate validation practices for the deep-sensing CRNS method, including fusion of supporting soil data, moisture profiles, and vegetation information, and to harmonise the different methods across scales, in a holistic and yet metrologically traceable approach. Furthermore, there is a need for 'the next logical step', i.e., for performing the data fusion of the multi-scale soil moisture measurements to generate high-quality, temporally, and spatially consistent soil moisture information, useful

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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:

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 will be developed. The measurement supply chain will be extended to outdoor conditions by transfer standards and an improved on-field sampling method developed.

New traceability scheme and validation practices for CRNS method: A traceability scheme for CRNS methodology will be developed. The neutron response functions of the CRNS devices will be validated using calculations and neutron reference fields. This will allow for an effective validation of current and upcoming

CRNS device designs. The combination of metrology for neutron radiation, 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, 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 will be 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.

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.

Outcomes and impact

Outcomes for industrial and other user communities

The calibration procedure developed in this project will allow manufacturers of hydro-meteorological equipment (used in the meteorological, hydrological, agricultural, environmental and related fields) to certify the performance of their instruments based on standard procedures. This would enable them to respond to the needs of national meteorological services for maintenance-reduced instrumentation and fully automated weather stations. The growth of the global automated weather station market is likely to result in significant financial benefits.

Manufacturers of laboratory equipment for instrument calibration will also benefit from the calibration procedure and metrological framework developed within this project, 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 development of the traceability scheme and validation practices for the CRNS method as part of this project, as well as the recommendations on networks design and validation practices, will support the existing and upcoming CRNS networks in Europe and worldwide. This positive effect will be in form of SI-traceable CRNS devices, more reliable and interoperable data sets from CRNS networks, harmonised data for further use in hydrology, meteorology, and agriculture. The improvements in the metrological basis of the CRNS method are also important for further joint initiatives such as Joint FAO and IAEA Programmes.

Organisations providing advice to policy makers (such as the European Union of Water Management Associations (EUWMA), the European Environment Agency (EEA)) will benefit from the calibration procedure and harmonisation of various soil moisture measurements developed in the project, as they will have access to local hydrological conditions that are interoperable and comparable on the European scale. This will provide them with improved soil and environmental scenario analysis for not only current purposes but also future planning of the managements of water and soil resources, e.g., in agricultural policies.

This project will directly liaise with industrial stakeholders via the formation of a Stakeholder Committee. This group will include representatives from agro-meteorological services, national meteorological services, WMO members of expert teams, regional instrument centres, manufacturers centres, and will help the project's results to directly impact such representatives.

In addition, this project will also produce and publish 3 good practice guides for end-users:

- Good practice guide for calibration practices for CRNS soil moisture data retrieval in outdoor field conditions covering on lateral scales ranging from 10^2 m to 10^3 m and to depths of up to 1 metre
- Good practice guide for harmonising soil moisture measurement methods to overcome temporal and spatial differences (lateral scales ranging from point scale to km scale) and the influence of other state variables such as air humidity and soil temperature affecting the measurements

- Good practice guide for interdisciplinary data fusion of soil moisture measurements on multiple scales

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 (CMCs) 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. TUBITAK will establish a new calibration service for soil moisture measurements. DTI will integrate the results of the project in its existing services related to field trials and plant technology (https://www.dti.dk/specialists/agrotech/36805). DTI will also offer new consultancy and laboratory services to the scientific community on the traceability of soil moisture measurement using point scale sensors. In general, 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 (e.g., TERENO, COSMOS-UK, eLTER) and worldwide (COSMOS, CosmOz, COSMOS-India). 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 will also host two one-day stakeholder events to disseminate results of the project and promote the uptake of the technology and measurement infrastructure developed. The first workshop will train participants from the stakeholder community, specifically those from hydro-meteo agencies, agrometeorological consortia, and manufacturers. The second one-day “Soil Moisture Workshop” will present and discuss the project results, including the project’s three good practice guides, to stakeholders, including WMO representatives, national meteorological and agro-meteorological representatives.

Finally, the project will provide output to the metrology and scientific communities via input to the EMN COO by interacting closely with the EMN COO network members. The consortium will also liaise with the EMN’s associated projects dealing with establishing the metrology for ECVs observation.

Outcomes for relevant standards

Currently, most of the guidance for soil moisture measurements in the field is contained in good practice guidelines (e.g., IAEA technical documents on field estimation of soil water content and on CRNS, Committee on Earth Observation Satellites (CEOS) good practice protocol for remote sensing, and methods for soil analysis by the American Society of Agronomy), 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 (INFCOMM), 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).

Members of the consortia sit in and chair relevant WMO expert teams and a 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).

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 generally 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, and enable more comparable data in space and time. 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 (such as an increase in crop yields) and reduction of water waste for irrigation and hence increased water availability. A reduction in maintenance costs for hydro-meteorological agencies and agro-meteorology consortia and users is foreseen. This project has the potential to increase the demand for such systems, possibly lowering their commercial costs.

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 ECVs prescribed by GSRN, soil moisture is one of the fundamental observed quantities for a reference site. The non-contact systems (CRNS) developed in the project will offer more reliable data and are nearly immune to maintenance and mechanical drifts and shocks, thus becoming a more robust 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.

The involvement of the consortium in BIPM and the WMO, at the operational level and in the supporting research, guarantees fast and efficient communication and feedback. Coordinating the efforts and avoiding duplication of work or contrasting conclusions, will increase the chances of successfully transferring the results into standardisation documents soon after the conclusion of the project. Improvements in traceability and better measurement facilities for soil moisture measurements, with lower and metrologically reliable uncertainty, will have direct impacts on the global environment which serves a healthy food system for people in the European Green Deal framework. Therefore, the project has an indirect impact on the health and quality of life of human society. As mentioned earlier, more reliable and traceable soil moisture observations are also the basis for supporting decision making in many water-related sectors, from irrigation management and planning to flood forecasting and early warnings.

List of publications

n/a

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

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