Final Public Report for 21GRD08 SoMMet
Metrology for multi-scale monitoring of soil moisture

Overview

Soil moisture affects agriculture, forestry, groundwater recharge, weather and climate, and greenhouse gas emissions. Numerous observation systems operate across spatial scales, but their measurements require harmonisation. The objective of this project was to develop novel metrological tools and to establish a metrological foundation for traceable, harmonised soil moisture measurements across lateral scales from decimetres to kilometres.

Primary metrological standards for determining soil water content in soil samples were developed and validated. Two soil-moisture transfer standards were developed and applied to improve traceability under outdoor conditions, supported by newly developed calibration facilities for harmonised testing and calibration of commercial point-scale sensors, now available to end users. Four commercial cosmic-ray neutron sensor (CRNS) types were characterised in neutron metrology laboratories and their digital-twin models validated. A novel concept coupling CRNS models with a digital twin of the outdoor environment was developed to predict CRNS sensor performance based on key environmental parameters, including soil moisture. Joint measurement campaigns delivered new datasets that supported improved harmonisation approaches and the development of a new multi-scale data-fusion concept.

The project outcomes will support manufacturers and end users of point-scale and CRNS sensors and, in the long term, improve the reliability, comparability, and interoperability of soil moisture assessments.

Need

The World Meteorological Organisation (WMO) defines soil moisture as one of the Essential Climate Variables (ECVs) that must be reliably monitored within its Global Climate Observing System. Soil moisture influences land–atmosphere interactions on both weather and climate timescales. Long-term storage and release of carbon in soils are strongly influenced by soil moisture: only healthy and adequately moist soils can act as a carbon sink in strategies for greenhouse gas mitigation and adaptation to climate change impacts. Soils are a cross-cutting theme within the European Green Deal, as the sectors of water management, agriculture, forestry, and biodiversity are inherently interdependent, increasingly so under ongoing climate change.

Soil moisture measurements at the point scale, performed by end users in agriculture and hydrology or by scientists dealing with soil moisture as an ECV, are typically carried out with contact sensors, which are invasive and subject to local heterogeneity and installation effects. The measurements are not representative of larger spatial scales relevant for many practical applications. To overcome this, complex sampling designs and interpolation methods can be implemented; however, associated uncertainties need to be reduced, and practical calibration guidelines developed. There is a lack of comparability and harmonisation among point-scale sensors under both laboratory and outdoor conditions, which calls for a robust metrological foundation.

Remote observation of the Earth via satellite missions can be used for continuous monitoring of soil moisture at kilometre scales. Nevertheless, intermediate-scale methods such as CRNS are needed to bridge the gap between point-scale measurements and satellite-based remote sensing. The CRNS methodology needs to be harmonised, and reliable calibration, validation, and characterisation methods developed. Overall, there is a need for improved comparability and harmonisation of soil moisture observations across spatial scales from centimetres to kilometres and temporal scales from minutes to days, using different measurement methods.

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European Partnership Co-funded by the European Union

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

METROLOGY PARTNERSHIP EURAMET

Objectives

The overall aim of this project was 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 were:

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, summarised 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

There are numerous soil moisture observation systems in use worldwide, ranging from invasive point-scale soil moisture sensors to large-scale remote sensing products. In addition, the more recent non-invasive, intermediate-scale soil moisture assessment method of cosmic-ray neutron sensing (CRNS) has found widespread use. Despite several initiatives, no harmonisation approaches compliant with metrological standards are currently available. This project has addressed this gap by developing the metrological tools needed for traceable and validated soil moisture measurements at the point and intermediate scales. For the first time, metrological tools for all three spatial scales have been considered in a holistic approach to harmonise soil moisture monitoring across scales. The overall objective and approach are illustrated in Figure 1.

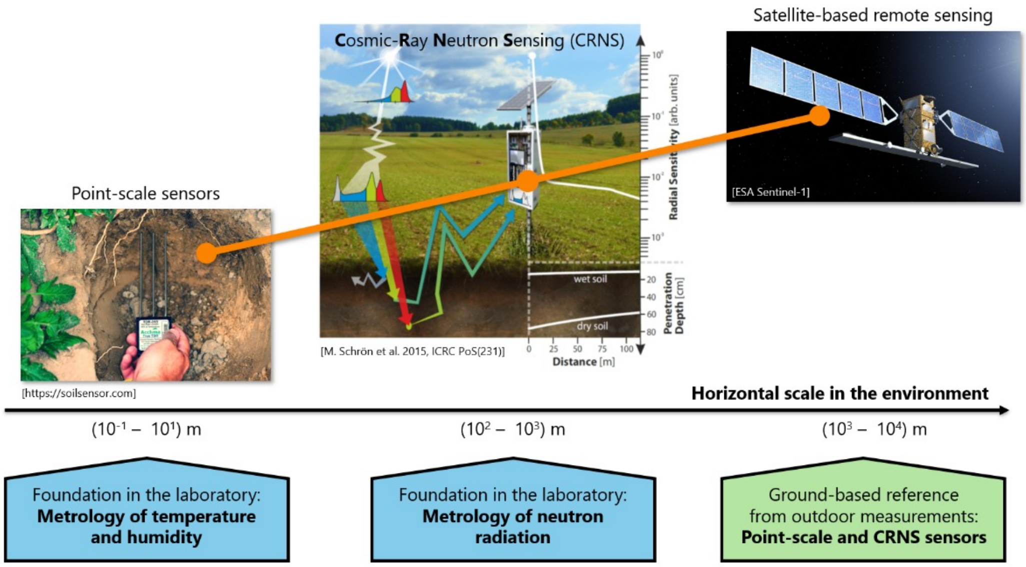

Figure 1: Scheme of the overall project objective. The metrological foundation of soil moisture measurements at the point and intermediate scales is established using temperature and humidity metrology and neutron radiation metrology, respectively. Commercial point-scale sensors are calibrated in temperature and humidity laboratories, while digital-twin models of cosmic-ray neutron sensors (CRNS) are validated in neutron laboratories. Further simulations of neutron radiation in the environment, together with soil sampling campaigns and reference neutron measurements, lead to a better understanding of the CRNS methodology and improved performance under outdoor conditions. Finally, comparison measurements at test field sites provide high-quality data for harmonisation and data fusion of soil moisture across multiple scales, including satellite-based soil moisture products.

Metrologically traceable methods for multi-scale soil moisture measurements

The project consortium developed an SI-traceability scheme describing how traceability is transferred from primary metrology standards, via transfer standards, to commercial point-scale soil moisture sensors and to CRNS sensors assessing field-scale soil moisture. The scheme was defined through discussions with soil moisture expert communities and the stakeholder committee, and an online survey organised by JV.

For point-scale sensors, the traceability chain lies in temperature and humidity metrology. For CRNS sensors, neutron radiation metrology applies, since CRNS measures naturally occurring environmental neutron radiation and its variations to infer intermediate-scale integral soil-moisture dynamics. To improve the CRNS methodology under outdoor conditions, both traceability chains—temperature and humidity, and neutron radiation—were combined.

Reference methods for soil water content determination were developed by DTI, TUBITAK and CMI. DTI and CMI adapted their existing primary-level standards for water content in materials to soil samples. TUBITAK developed its primary-level standard based on evolved water vapour detection. The systems, including uncertainty budgets and calibration procedures, were characterised and validated using mineral and organic soils. DTI developed a mobile transfer standard based on the flow-based Loss-on-Drying (fLoD) method and validated it against the primary standard using organic and inorganic soils. In parallel, TUBITAK designed and built a novel Proximal Soil Moisture Sensor (PSMS), a portable transfer standard in the visible–near-infrared–short-wave infrared (Vis–NIR–SWIR) range based on fibre-coupled spectrometers; it complies with IEEE soil spectroscopy standards and enables proximal sensing of surface soil moisture in laboratory and outdoor conditions.

DTI, together with TUBITAK, CMI and LNE-CETIAT (a French metrology laboratory that was not part of the project consortium), performed the EURAMET Pilot Study P1685 "*Intercomparison of Soil Moisture Measurement*". Primary standards for water content in soil samples were successfully compared using reference materials and soil samples. All primary standards demonstrated bilateral agreement. The soil samples showed excellent homogeneity and stability during transport, indicating strong potential for future comparison studies.

The target value of 5 % standard relative uncertainty for soil water content measurement under laboratory conditions was met, and Objective 1 was thereby achieved.

New traceability scheme and validation practices for CRNS method

The neutron metrological framework was implemented for SI-traceable validation of commercial cosmic-ray neutron sensing (CRNS) devices under laboratory conditions. Four commercial state-of-the-art CRNS sensor types, currently used in operational and emerging CRNS networks in Europe and worldwide, were selected for detailed investigation. The four commercial systems are based on different neutron detection principles: Finapp 3 (Finapp S.r.l.; lithium-6 scintillator), S1 (StyX Neutronica GmbH; boron-10-lined gaseous detector), CRS-1000 (Hydroinnova LLC; helium-3 proportional counter) and CRS-2000/B (Hydroinnova LLC; boron trifluoride, BF_3, proportional counter). CMI, CIEMAT, PTB, SMU, ASNR and UHEI developed digital twins of these systems to support Monte Carlo simulation-based neutron transport calculations. Such cluster-supported calculations quantify and predict a device's neutron detection efficiency (sensitivity) across the relevant neutron-energy range.

The CRNS digital-twin models were validated through systematic experimental campaigns in the neutron reference fields of CIEMAT, CMI, PTB, SMU and ASNR. The CRNS systems were irradiated in well-defined, SI-traceable neutron fields to evaluate performance and investigate systematic effects. These campaigns were challenging due to the large size and high neutron sensitivity of the CRNS systems, requiring purpose-tailored irradiation configurations in the metrology laboratories. The validated models were then used to calculate neutron response functions predicting sensor performance across neutron-energy ranges. These joint efforts represent the first systematic laboratory characterisation of CRNS sensors—typically deployed outdoors to monitor intermediate-scale soil moisture dynamics—using laboratory-based ("artificial") neutrons. This marks a milestone in improving CRNS methodology and harmonising community practices by establishing a robust metrological foundation. In subsequent project steps, the validated CRNS models were used to assess sensor performance under outdoor conditions.

Building on this experience, PTB and UHEI explored several candidate concepts for a novel neutron reference field to meet the needs of SI-traceable and cost-effective characterisation and validation of current and future CRNS designs. In summary, objective 2 was achieved.

New on-field comparison campaigns on local and remote sensing

The project brought together metrology experts and specialists in point-, intermediate- and large-scale soil moisture observations. New soil moisture datasets were collected at established experimental field sites operated by the project participants, selected for their relevance to calibrating and validating soil moisture retrieval from CRNS and remote sensing.

Gravimetric soil moisture measurements at three soil physics laboratories linked to high-level project sites (ATB Marquardt near Potsdam, Germany – UP DE; Bondeno in Northern Italy – UNIBO; Apulian Tavoliere in Southern Italy – CNR) were validated using DTI's transfer standard for soil water content. Field laboratories collected pairs of soil samples from up to ten locations per site: one sample was analysed locally, while its counterpart was frozen, transported in temperature-monitored packaging and measured at DTI to minimise biological alteration of the water content. Bilateral comparisons showed that all three sites were consistent with the DTI reference, demonstrating robust measurement systems suitable for SI-traceable soil moisture measurements across the project field sites.

Long-term datasets were collected with commercial point-scale sensors characterised in metrology laboratories. In parallel, CRNS neutron measurements were used to derive integral soil moisture dynamics; the CRNS footprint (sensing volume), systematic effects and retrieval uncertainty were investigated. TUBITAK, supported by CNR, conducted a dedicated field campaign to test its novel Proximal Soil Moisture Sensor for SI-traceable surface soil moisture measurements under outdoor conditions.

UHEI and UFZ modelled the high-level sites using the URANOS neutron simulation framework to create detailed digital twins and simulate environmental neutron radiation as a function of key environmental variables and site settings, including soil moisture. During CRNS data-taking, UFZ, PoliMi, ASNR and PTB performed dedicated outdoor neutron measurement campaigns with additional detection systems, providing reference or supplementary datasets used to benchmark and validate URANOS predictions. Combining laboratory-validated CRNS neutron response functions with URANOS-based site models, UHEI developed the concept of a "virtual reference CRNS neutron field". This novel concept is generally applicable to other CRNS sites and represents a significant advancement in CRNS methodology, fostering its future applications. In summary, Objective 3 was achieved.

Cross-disciplinary harmonisation system for soil moisture monitoring

Based on newly collected and historical datasets, improved procedures were developed for harmonising soil moisture assessments across temporal scales and lateral scales from point to kilometre. UNIBO, UKCEH and CNR reviewed and compared methods to characterise the spatial and temporal variability of soil moisture observations, assessed using state-of-the-art Earth Observation concepts, namely the scale triplet (spacing, extent, support) and representativeness. Current QA/QC (Quality Assurance/Quality Control) methods for soil moisture observations were reviewed for their applicability to dynamic uncertainty estimates. QC criteria for ground-based soil moisture measurements, as implemented at international level (e.g., in the International Soil Moisture Network, ISMN), were adopted. The information content of each soil moisture measurement method was quantified and its strengths and weaknesses assessed.

UNIBO, CNR, UKCEH, IAPAN, DTI and CTU reviewed harmonisation methods used for soil moisture and other environmental variables across multiple scales. The most promising methods were selected, applied to the new project datasets, and evaluated based on harmonised results and uncertainties, data requirements, and practical feasibility. The selected procedures were consolidated into a workflow, tested on historical and project-site datasets, and compiled as recommendations in a good practice guide.

IAPAN, CNR and UNIBO reviewed existing soil moisture data fusion practices and categorised them into four families: geostatistical, Bayesian, minimum variance and machine learning. Their advantages and limitations were summarised and discussed with experts, leading to a shortlist of methods for further investigation. CNR processed relevant Earth Observation datasets to complement ground-based measurements, including time series of surface soil moisture saturation index at 1 km spatial resolution from Copernicus Sentinel-1 and additional Sentinel-1 radar image series over the project sites. Using CNR's soil moisture retrieval algorithm SMOSAR (Soil MOisture retrieval from multi-temporal SAR data), volumetric surface soil moisture maps were derived from Sentinel-1 backscatter for the data fusion study. CNR, IAPAN and UNIBO then fused historical and new multi-scale observations at the high-level test sites and developed a proof-of-concept data fusion workflow integrating satellite and ground-based datasets, documented in a good practice guide with recommendations for calibration/validation of remote-sensing soil moisture products using CRNS systems and clusters. Objective 4 was thereby achieved.

Outcomes and impact

Key dissemination and communication activities

The consortium submitted 14 open-access papers to peer-reviewed scientific journals, such as *Hydrology and Earth System Sciences*, *Remote Sensing*, *Geoderma* and *IEEE Transactions on Instrumentation and Measurement*. The publications are listed in the next section. Project participants gave a total of 54 oral and poster presentations at 31 conferences and workshops.

In September 2023, INRIM organised the International Conference MMC 2023: Metrology for Meteorology and Climate, bringing together metrologists, meteorologists from national services and members of WMO expert teams. In June 2025, INRIM co-organised the 2025 edition of MMC. Both events included a Soil Moisture Workshop, which was used to promote the project and disseminate its outcomes. In addition, the project was disseminated at topical events such as the European Geosciences Union (EGU) General Assembly (2024 and 2025), IMEKO 2024 XXIV World Congress, the American Geophysical Union (AGU) Annual Meeting 2024 and the TEMPMEKO-ISHM 2025 Symposium.

Dissemination to a broader audience took place during the two-day exhibition "*Woche der Umwelt*" (Week of the Environment) in June 2024, hosted by the President of Germany, Frank-Walter Steinmeier, in the gardens of Bellevue Palace, attracting around 12,000 visitors. In January 2025, DTI organised a one-day hybrid training course in conjunction with the M27 project meeting at DTI in Taastrup near Copenhagen; 62 participants attended, 20 in person. The course contributions were recorded and are publicly available on Zenodo. The project website will continue to be maintained as a centralised dissemination channel for project outcomes.

Outcomes for industrial and other user communities

The reference methods for determining soil water content in soil samples will benefit soil-moisture measurement equipment manufacturers and end users, including those conducting laboratory soil analyses and those using point-scale sensors outdoors. These communities are expected to be the first adopters of the methods. The measurement standards and calibration procedures developed in this project will enable manufacturers to certify instrument performance using standardised procedures, strengthening the market for soil moisture sensors and supporting more interoperable equipment and services. This will, in turn, aid harmonisation in application areas such as weather monitoring and forecasting, as well as precision farming. The new services offered by DTI and TUBITAK will be promoted via their communication channels and websites to engage commercial stakeholders and end users of point-scale soil moisture sensors.

The validation of four different commercial CRNS sensor types in neutron metrology laboratories, together with an improved understanding of CRNS performance under outdoor conditions, will support wider uptake of CRNS for existing and emerging applications, including hydro-meteorological monitoring and smart agriculture. The possibility to validate current and future CRNS system designs in an SI-traceable way will support sensor manufacturers and, in turn, their users. These developments will directly benefit user communities, including agro-meteorological services, national meteorological services, WMO expert team members, and instrument manufacturer and regional instrument centres.

<u>Outcomes for the metrology and scientific communities</u>

SI-traceable metrology for water content in materials has been partially established over the last decade. However, currently no countries have BIPM Calibration and Measurement Capabilities for moisture measurement, and SI-traceable measurements of soil moisture at the primary level have, to our knowledge, not been reported. A key outcome of this project is the establishment of primary-level soil moisture measurements with associated uncertainty budgets. An inter-laboratory intercomparison of primary standards for water content in soil samples was organised and registered as the EURAMET Pilot Study P1685 "*Intercomparison of Soil Moisture Measurement*". Using soil samples and reference materials, the comparison showed bilateral agreement among all primary standards, and the soil samples exhibited excellent homogeneity and stability during transport, supporting future comparisons. Validation of three soil physics laboratories at high-level project sites—based on paired sampling analysed locally and at DTI using a portable transfer-standard reference setup—demonstrated the suitability of the metrology systems for SI-traceable soil moisture measurements along the traceability chain. In addition, TUBITAK's novel Proximal Soil Moisture Sensor, a portable Vis–NIR–SWIR transfer standard based on fibre-coupled spectrometers and compliant with IEEE soil spectroscopy standards, enables proximal sensing of surface soil moisture under laboratory and outdoor conditions.

Neutron radiation metrology contributed to the CRNS community by enabling SI-traceable validation of CRNS systems in neutron reference fields. PTB also developed a portable, weather-resistant neutron Bonner sphere spectrometer for automated long-term outdoor operation, serving as a neutron metrology transfer standard. It provides high-quality reference data for determining the full neutron energy spectrum across a wide range of environmental conditions. Future campaigns will deliver additional reference neutron data to investigate and quantify CRNS systematic uncertainties in specific outdoor settings. This support from neutron metrology is key to harmonising the CRNS scientific and user community.

Together, these outcomes improve sensor performance across scales, provide more reliable uncertainty budgets, and enable more interoperable datasets. The resulting long-term datasets support the missions of national and international (agro)meteorological services and data centres such as the International Soil Moisture Network (ISMN) and align with the calls of CEOS (Committee on Earth Observing Satellites) for reliable datasets based on a harmonised ground reference site concept, following the Fiducial Reference Measurement (FRM) principles. For example, the European Space Agency-funded FRM4SM project (Fiducial Reference Measurements for Soil Moisture) is developing protocols to qualify ground-based soil moisture measurements as "fiducial" references for remote sensing. The outcomes of this project will be communicated to the FRM4SM expert community, and potential collaboration will be pursued.

<u>Outcomes for relevant standards</u>

Most guidance on field soil moisture measurements is currently provided through good practice guidelines, with limited formal validation and standardisation. Standardised procedures, supported by suitable calibration devices, would benefit both manufacturers and users of soil moisture instruments. At present, wider use is constrained by the lack of standardised calibration procedures and by limited metrological comparison and harmonisation across sensor types and manual gravimetric/volumetric soil moisture measurements.

The project's outcomes will support standardisation activities in CEN TC444 Environmental Characterisation WG5 Physical tests and ISO TC 190 Soil quality WG1 Soil and Climate Change SC3 Chemical and physical characterisation. The project was presented to the WMO Standing Committee on Measurements, Instrumentation and Traceability (WMO SC-MINT), the WMO Commission for Observation, Infrastructure and Information Systems (WMP INFCOM), the WMO Global Climate Observing System (GCOS) and its Surface Reference Network (GSRN), the WMO SC-MINT Expert Team on Measurement Uncertainty (ET-MU), the EURAMET Technical Committee for Thermometry (TC-T) and the BIPM Consultative Committee for

Thermometry Working Group for Humidity (CCT-WG-Hu). Where appropriate, outcomes will be incorporated into guidance material, including updates to the WMO '*Guide to Meteorological Instruments and Methods of Observation'* (WMO Guide No. 8).

Longer-term economic, social and environmental impacts

The project's new methods, technologies and knowledge will support harmonisation and interoperability, and thereby increase uptake of soil moisture measurements across scales. Impacts are expected for companies providing services in hydrometeorological warnings, water resources management, flood control, agriculture and hydropower generation, where decisions on industrial system configuration and operation (including in real time) rely on hydrometeorological monitoring and data processing. Using calibrated soil moisture instruments alongside other meteorological observables will improve decision-making by basing it on traceable measurements. More reliable data will enable weather services, local agrometeorological consortia and other users to be informed promptly about drought and flood risk, supporting effective and timely warnings. The main economic impact is twofold: more reliable irrigation planning, benefiting agricultural production, and reduced irrigation water waste, increasing water availability.

The improved metrological basis of the CRNS methodology is expected to positively impact CRNS networks in Europe and worldwide and foster uptake in applications requiring integral field-scale soil moisture monitoring (e.g. agriculture and hydrology). Given limited traceability and data quality in historical observations, WMO's GCOS is preparing the GCOS Surface Reference Network (GSRN). Soil moisture is among the Essential Climate Variables for GSRN reference sites, and it is expected that, alongside point-scale sensors, a CRNS-type sensor will be included in the reference-site design. In parallel, national meteorological services in Europe are establishing national-scale CRNS networks; their harmonisation is a logical next step towards an integrated soil moisture observing system.

As soil moisture is one of the Essential Climate Variables, reliable monitoring will remain crucial for weather forecasting, climate observations, and climate change mitigation and adaptation, with its relevance expected to increase. The project outcomes will support these long-term missions.

List of publications

1. Emamalizadeh, S. et al (2024) 'Comparison of Soil Water Content from SCATSAR-SWI and Cosmic Ray Neutron Sensing at Four Agricultural Sites in Northern Italy: Insights from Spatial Variability and Representativeness', *Remote Sensing*, 16(18) p. 3384. Available at https://doi.org/10.3390/rs16183384
2. 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', *Geoscientific Instrumentation, Methods and Data Systems*, 13(1) p. 9-25. Available at https://doi.org/10.5194/gi-13-9-2024
3. Klahn, E. A. et al (2025) 'Establishing SI-traceable on-site calibration of point scale soil moisture sensors', *Measurement: Sensors*, Volume 38, p. 101523. Available at https://doi.org/10.1016/j.measen.2024.101523
4. Li, G. et al (2025) 'Metrology for climate action', *Measurement: Sensors*, Volume 38, p. 101850. Available at https://doi.org/10.1016/j.measen.2025.101850
5. Nasibov, H. (2024) 'Evaluation of Focus Measures for Hyperspectral Imaging Microscopy Using Principal Component Analysis', *Journal of Imaging*, 10(10) p. 240. Available at https://doi.org/10.3390/jimaging10100240
6. Szewczak, K., Łukowski, M. (2024) 'Medium-Scale Soil Moisture Retrievals Using an ELBARA L-Band Radiometer Using Time-Dependent Parameters for Wetland-Meadow-Cropland Site', *Remote Sensing*, 16(12) p. 2200. Available at https://doi.org/10.3390/rs16122200
7. Vykydal, Z. et al (2026) 'Monte Carlo simulation and experimental validation of the Finapp Model 3 cosmic-ray neutron sensor', *Meas. Sci. Technol.* 37 015901. Available at https://doi.org/10.1088/1361-6501/ae2649
8. Köhli, M. (2026) 'Soil Moisture Measurements by Cosmic-Ray Neutron Sensing: A Critical Review', *Geoderma* 465, p. 117626. Available at https://doi.org/10.1016/j.geoderma.2025.117626

List of technical deliverables and the data management plan

Deliverable number	Title	Confidentiality status	Clickable links to 'Public' documents
D1	Report on the calibration of soil moisture measurement devices using a primary method, based on evolved water vapour detection, and transfer standards, such as "standardised" loss on drying (LoD) or fibrecoupled spectrometers, to ensure SI-traceable point-scale soil moisture measurements with uncertainties of 5 % under laboratory conditions	PU - Public, fully open	https://doi.org/10.5281/zenodo.18788813
D2	Report on the traceability scheme and uncertainty model for validation of neutron response functions of CRNS neutron-measuring devices under laboratory conditions	PU - Public, fully open	https://doi.org/10.5281/zenodo.18798838
D3	Report on the comparison and validation of existing neutron transport models used to interpret CRNS signals measured under outdoor conditions	PU - Public, fully open	https://doi.org/10.5281/zenodo.18803623
D4	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	PU - Public, fully open	https://doi.org/10.5281/zenodo.18804194
D5	Report on the comparison of soil moisture measurement methods and their different sensing domains (local and remote) including details on the constraints and accuracy of the methods and requirements for harmonisation.	PU - Public, fully open	https://doi.org/10.5281/zenodo.18804770
D6	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	PU - Public, fully open	https://doi.org/10.5281/zenodo.18805234
D7	Report on the comparison of the existing data fusion practices for soil moisture measurements on multiple lateral (from 10^{-1} m to 10^3 m and to depths of up to 1 metre) and temporal (from hours to days) scales to assess the soil moisture with traceable relative uncertainty of 20 % or better	PU - Public, fully open	https://doi.org/10.5281/zenodo.18806979
D8	Good practice guide for interdisciplinary data fusion of soil moisture measurements on multiple scales	PU - Public, fully open	https://doi.org/10.5281/zenodo.18807290
n/a	Data management plan	PU - Public, fully open	https://doi.org/10.5281/zenodo.18783106

Project start date and duration:	01 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. ASNR, 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:
Associated Partners: 18. UKCEH, United Kingdom		