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Defining soil moisture and calibrating point-scale sensors

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MMC 2025: SoMMet Soil-Moisture
Workshop

Moisture in materials / Soil moisture

- Soil Moisture = Water in soil
- Essential Climate Variable (ECV)
 - Climate
 - Agriculture and forestry
 - Emissions
- Project on moisture in materials
 - 2013 – 2016: METefnet, new primary standards for moisture in solids
 - 2020 – 2023: BIOFMET, moisture transfer standards for biofuels
 - 2022 – 2025: SoMMet, metrology for moisture in soil
- SoMMet project 2022-2025
 - Fundamental metrology on different scales/techniques
 - Point-scale sensing (calibrations)
 - CNRS (neutrons)
 - Remote sensing (satellites)
 - Harmonization and Data fusion

The measurand

- Soil moisture
 - Soil water content = how much water
 - Soil water potential = how hard is it to extract water → plants
- Soil water content (SWC):
 - Volumetric water content, θ_v
 - Gravimetric water content, θ_m

- Most commonly used metric is volumetric water content (VWC, θ_v)

$$\theta_v = \frac{V_{\text{water}}}{V_{\text{soil, wet}}}$$

- But most reference measures water mass fraction (θ_m)

$$\theta_m = \frac{m_{\text{water}}}{m_{\text{soil, wet}}}$$

$$\theta_v = \frac{\rho_{\text{soil, bulk}} \cdot m_{\text{water}}}{\rho_{\text{water}}(T) \cdot m_{\text{soil, dry}}} = \frac{\rho_{\text{soil, bulk}}}{\rho_{\text{water}}(T)} \theta_m$$



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What is traceability in
metrology?

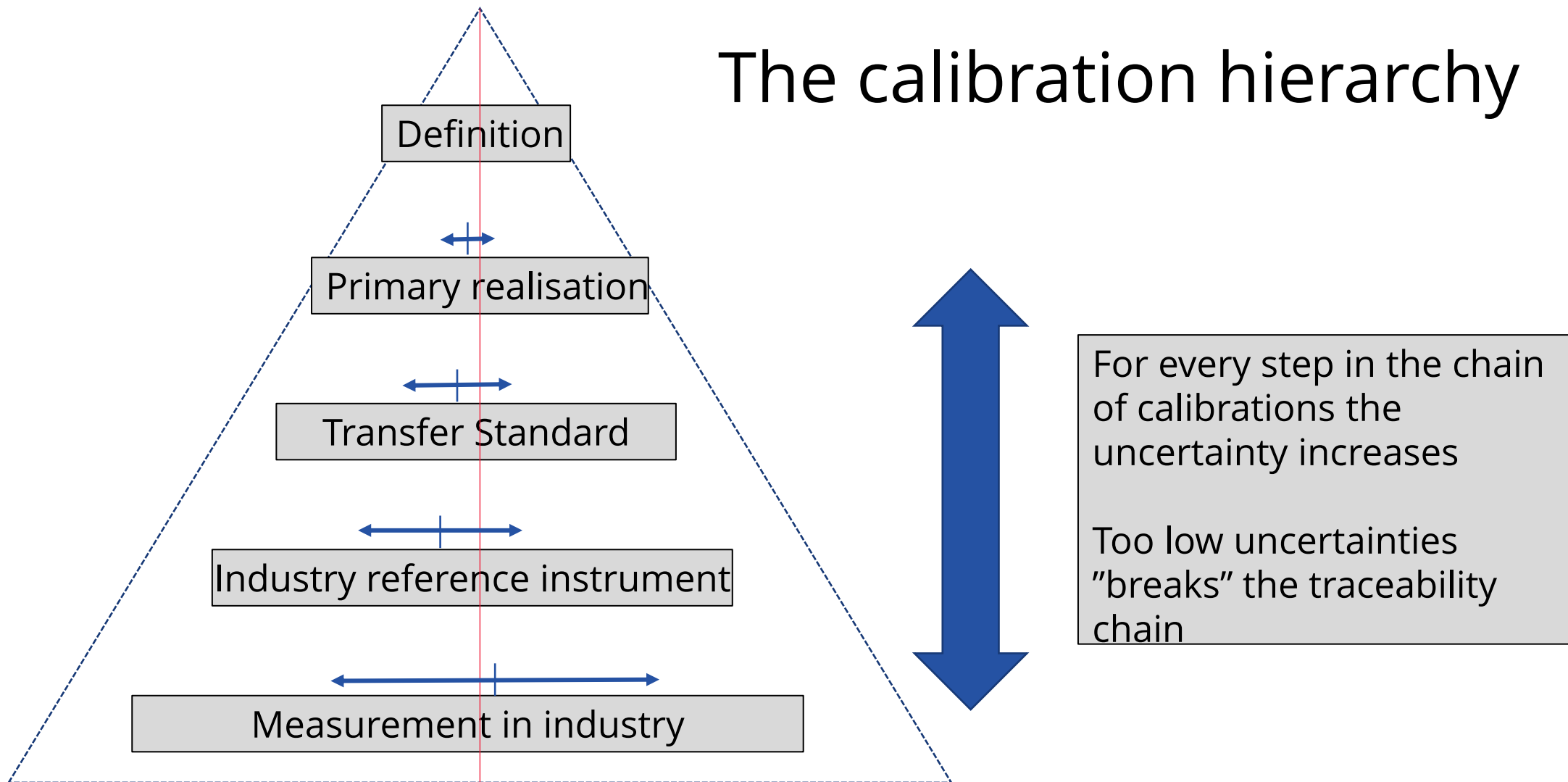


Metrological Traceability

- Metrological traceability is a property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty
- Measurement uncertainty ensures that a measurement result is related to a reference on a “higher level” that in the end is compared with a primary realization of the unit – measurement uncertainty is a measure of the quality of a measurement.
- Thus, traceability is needed in order to make trustworthy measurements on all levels independent of method or instrument type.

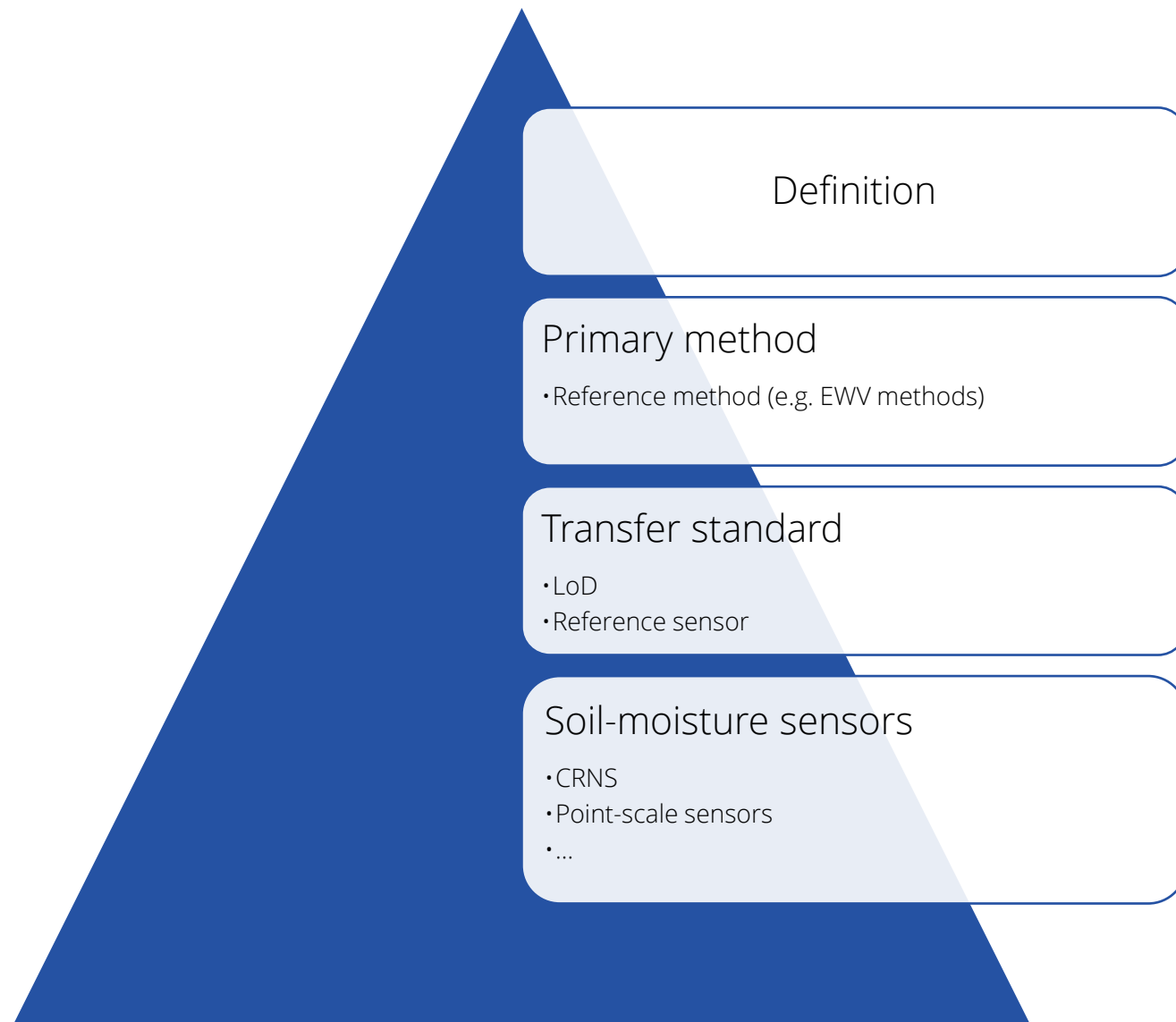


The calibration hierarchy



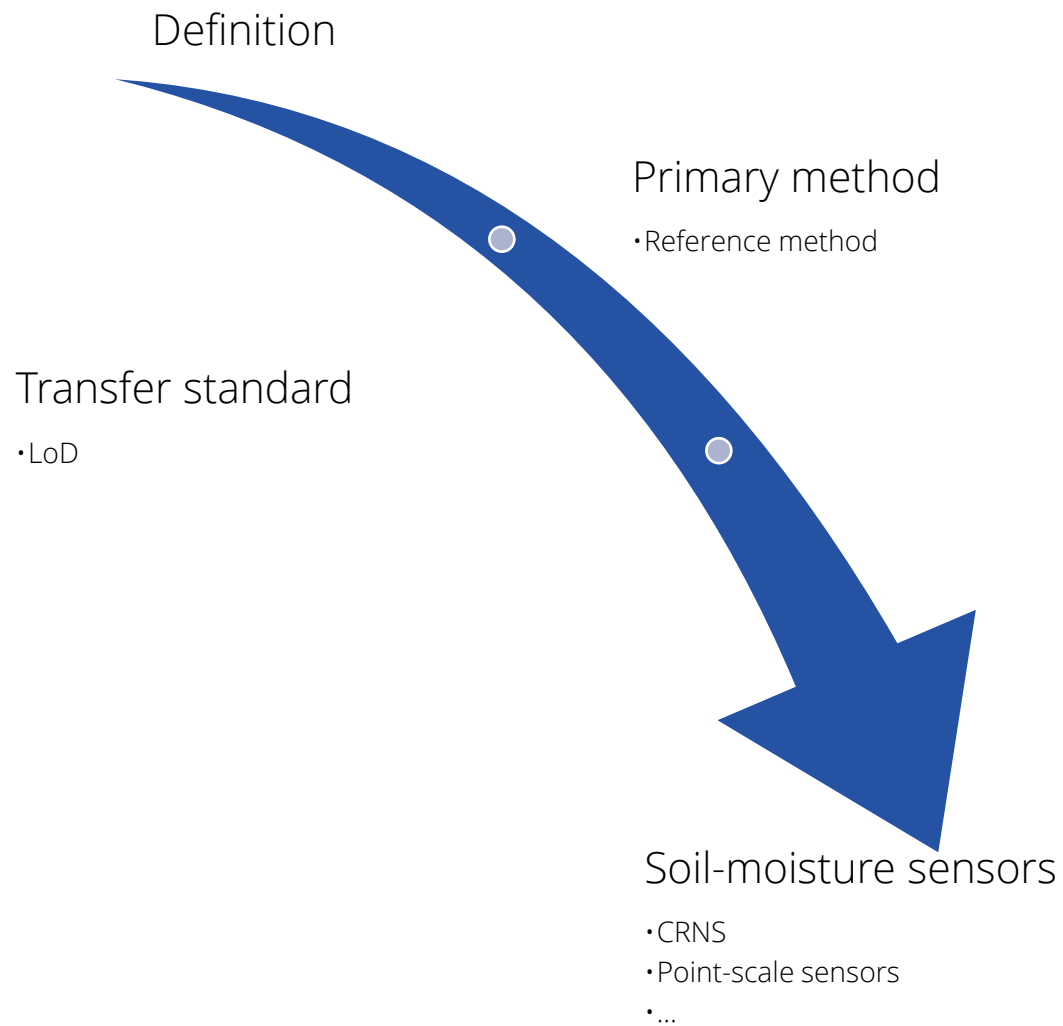


Soil-moisture metrology traceability





Soil-moisture metrology dissemination





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Step 1: Definition

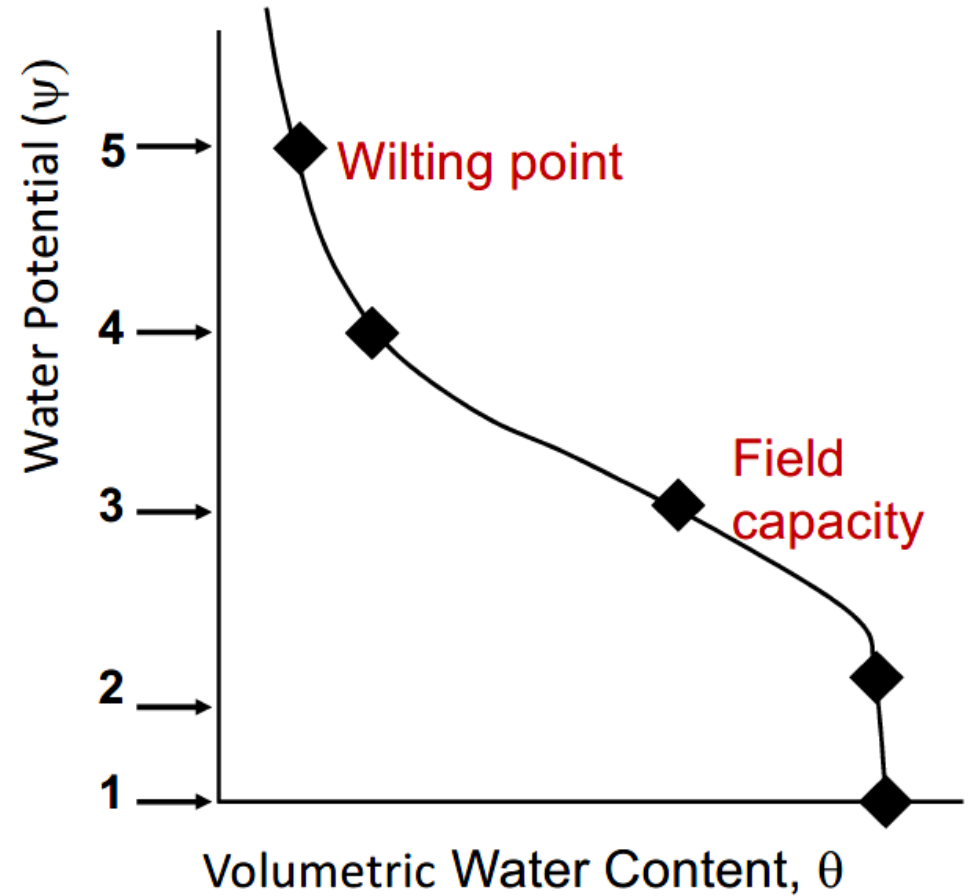


What is soil moisture?

✓ Water content

- Volumetric
- Gravimetric

○ Water potential





Measured quantity: Water content / Fraction or ratio / Wet or dry basis?

1. Water (or moisture) content

- Proportion of water in sample
- = mass of water
- = m_w
- Unit: kg

2. Water mass fraction

- Proportion of water in wet matrix (i.e. wet sample)
- = wet basis
- = $m_w/m_{wet\ sample}$
- Unit: Dimensionless, e.g. %, ppm, ...

3. Water mass ratio

- Ratio of water to dry matrix (i.e. dry sample)
- = dry basis

- = $m_w/m_{dry\ sample}$
- Unit: Dimensionless, e.g. %, ppm, ...

4. Water volume fraction (I)

- Ratio of water to (wet) matrix volume
- Requires sample density, ρ , or volume, V
- = $m_w/V_{sample} = \frac{m_w}{m_{sample}} \cdot \rho_{sample}$
- Unit: kg/m³, or g/L, ...

5. Water volume fraction (II)

- Ratio of water to (wet) matrix volume
- Requires sample density, ρ , or volume, V
- = $V_w/V_{sample} = \frac{m_w}{m_{sample}} \cdot \frac{\rho_{sample}}{\rho_w}$
- Unit: cm³/cm³, or g/L, ...



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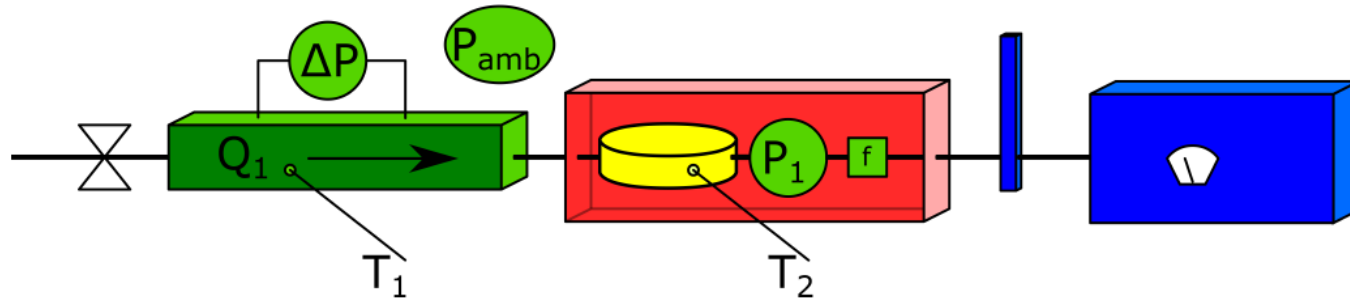
Step 2: Primary method



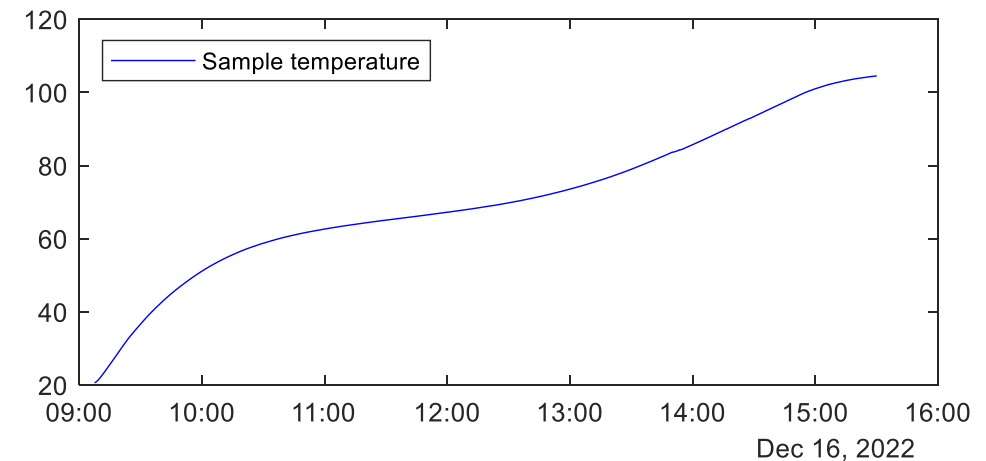
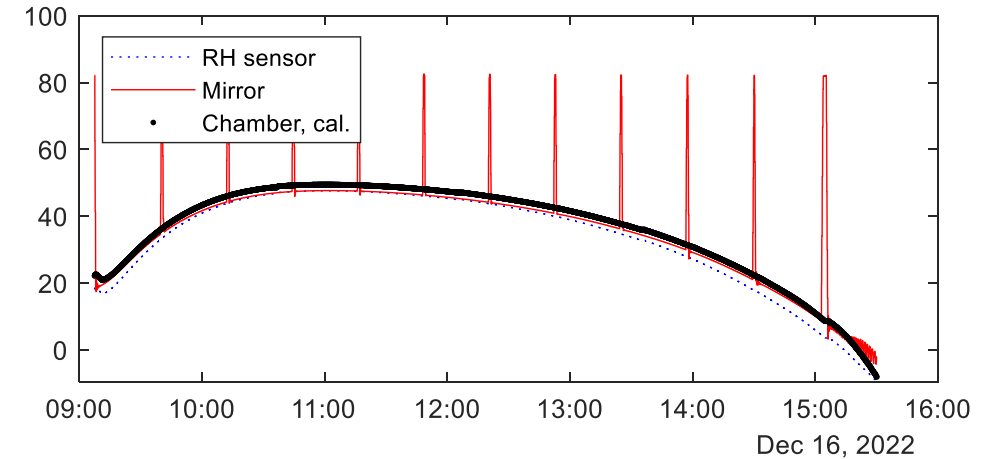
Primary method ...

1. Specific detection of water
2. Traceable via other physical quantities

DTI REFERENCE METHOD FOR WATER CONTENT (EWV-DP)



- Based on Evolved Water Vapour (EWV)
- Basic principle
 - Sample is dried in flow of dry air
 - Measure
 - Humidity (= Evolved water vapour)
 - Air flow
 - Water content = Flow $\times$ Absolute humidity
- Advantage: Specific water detection, Traceable
- Disadvantages: Single point (place, time), cumbersome, destructive



water content equals $21.75 \text{ g} \pm 0.49 \text{ g}$





Uncertainty of DTI reference method

Air supply:

- Laminar flow element:	6.2 ml/min
- Differential pressure transducer:	63 mPa
- Laminar flow element temperature:	11 mK
- Ambient pressure:	19 Pa
- Chamber temperature:	11 mK
- Gauge pressure:	12 Pa

Water detection:

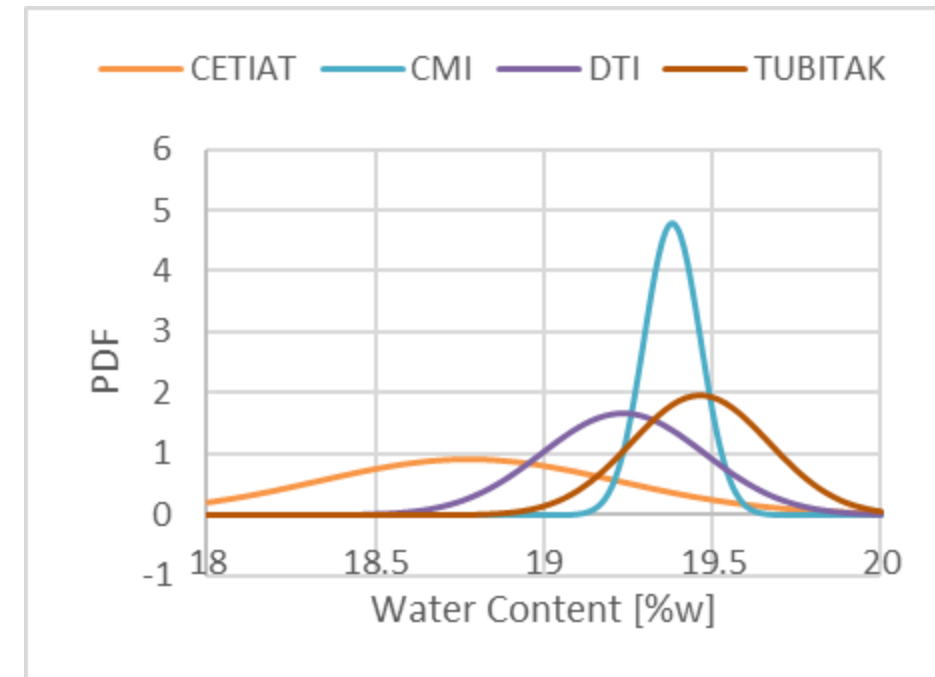
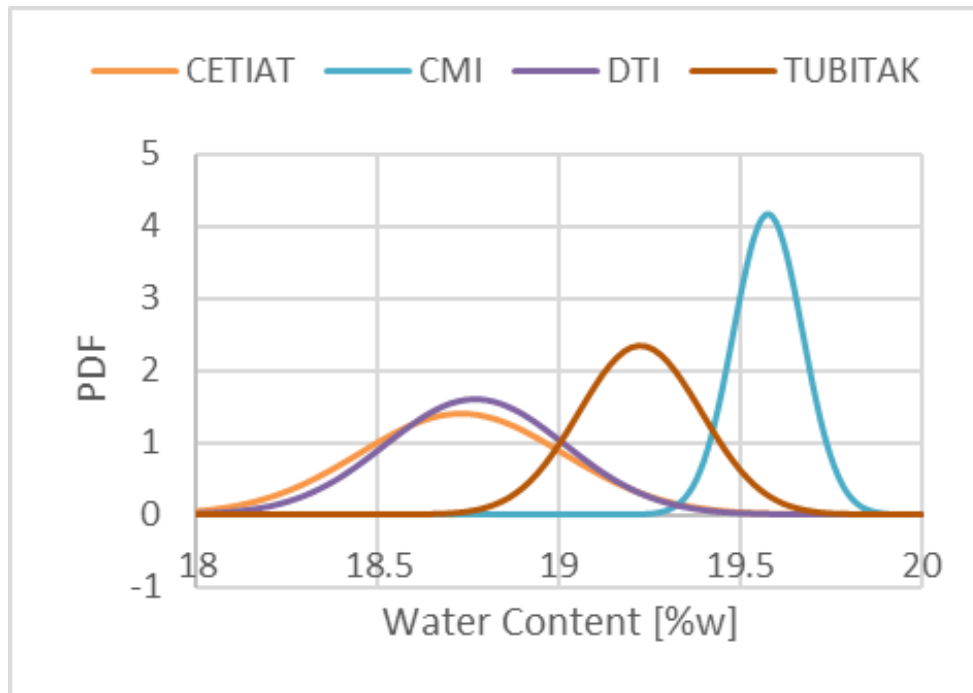
- Dew point hygrometer:	65 mK
- Capacitive humidity meter:	70 mK
- Vapor pressure formulation:	35 mK
- Residual water content:	0.010 g



Validation of primary methods

EURAMET project 1685: Pilot study: Intercomparison of Soil Moisture Measurement (ongoing)

- DTI, CMI, TUBITAK, CETIAT
- Organic (left) or Inorganic (right) samples



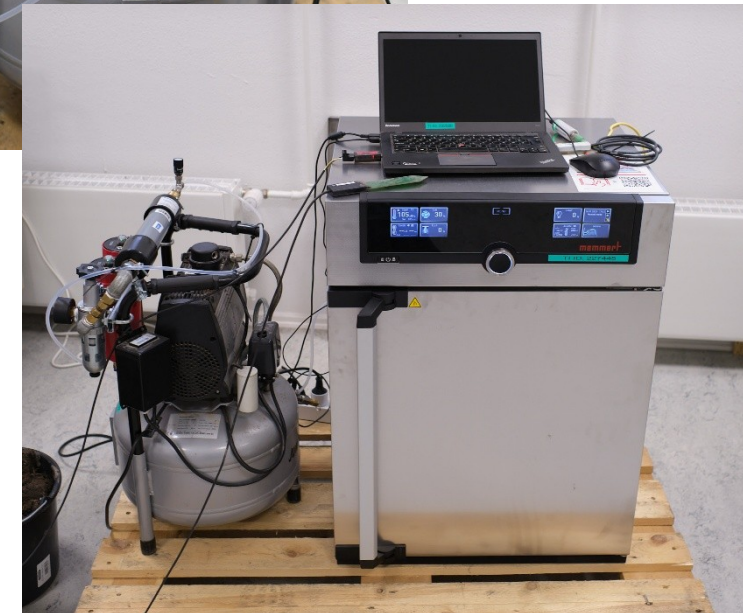
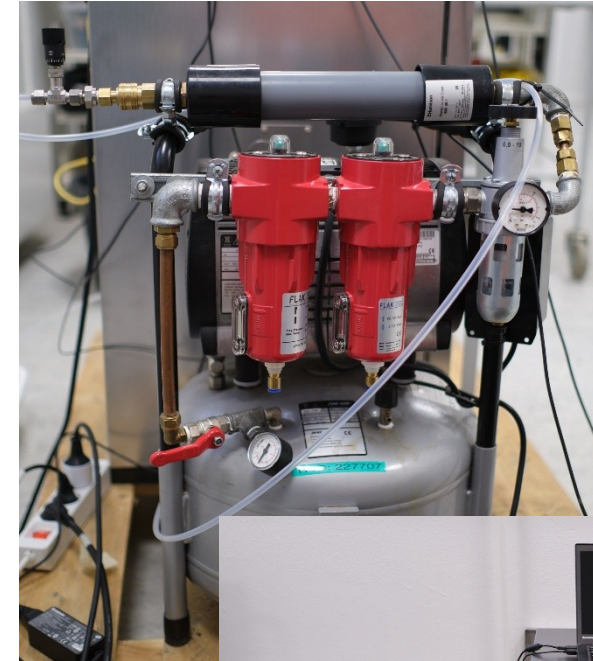


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Step 3: Transfer standard

DTI transfer standard based on LoD

1. Main measurement principle: Water content = mass loss (LoD)
2. Dissemination of traceability: Transfer standard
 - (Trans-) portable
3. Using dry air ($T_{dp} \leq -20\text{ °C}$) for analysis
 - Can extract more water from sample at a given temperature
 - Can use lower temperature (less degradation of organic compounds)
4. Setup controlled by humidity of drying air
 - Reduced risk of "over drying"
 - Additional water-content estimate (= air flow $\times$ water content)



DTI transfer standard: Calibration

- Comparison with primary reference

ORGANIC SOIL			INORGANIC SOIL		
Sample ID	Result, %	u , % ($k=1$)	Sample ID	Result, %	u , % ($k=1$)
107	19.10	0.03	7	19.39	0.03
121	18.88	0.03	14	19.45	0.03
128	19.22	0.03	21	19.52	0.03
135	18.94	0.03	28	19.35	0.03
149	19.04	0.03	35	19.44	0.03
156	18.89	0.03	56	19.48	0.03
170	19.23	0.03	70	19.32	0.03
Value, %			Value, %		
19.04			19.42		
u ($k=1$), %			u ($k=1$), %		
0.04			0.03		

	DUT	DUT	Ref.*	Ref.*	Error**	Combined	Ratio	Ratio
	Value, %	u ($k=1$), %	Value, %	u ($k=1$), %	Value, %	u ($k=1$), %	DUT/Ref	u ($k=1$), %
ORGANIC SOIL	19.04	0.04	18.77	0.25	0.27	0.25	1.015	0.014
INORGANIC SOIL	19.42	0.03	19.23	0.24	0.19	0.24	1.010	0.013

Validation of field laboratories using transfer standard (ongoing)

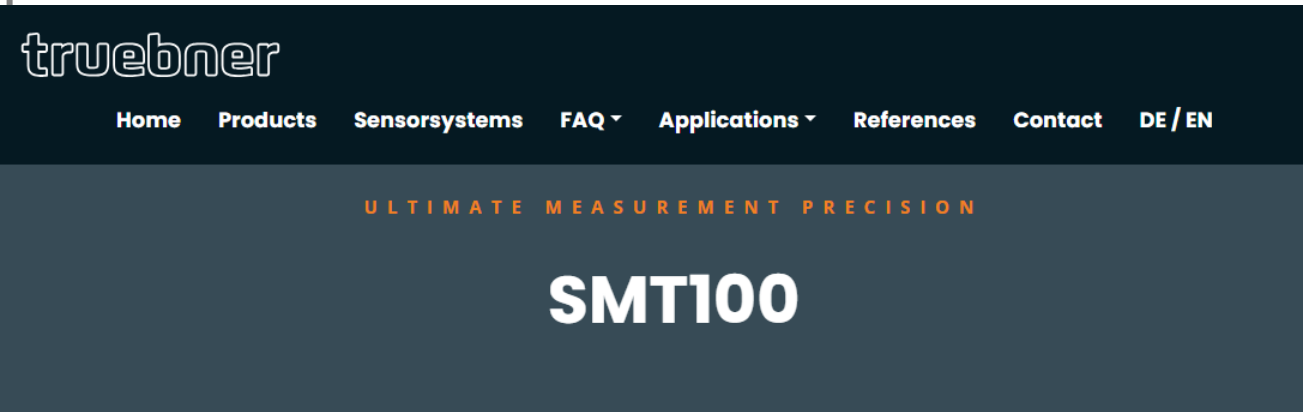
- 2x 10 samples from each field
- $\frac{1}{2}$ → Field lab (LoD)
- $\frac{1}{2}$ → Transfer standard



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Step 4: Point-scale sensors

Point-scale sensor: Example



- Truebner SMT100
 - <https://www.truebner.de/en/smt100.php>
- Measurement principle:
 - TDT (time domain Transmission)
- Specifications:



The SMT100 is a world class soil moisture sensor with outstanding accuracy for demanding applications in science and precision agriculture. Researchers and farmers have trusted the sensor for over 10 years.

For unparalleled compatibility with data loggers and controllers the SMT100 is available with the following interfaces:

- RS-485: TBUS/ASCII or Modbus
- SDI-12
- Analog voltage output: 0-10 V and customer specific voltage ranges like 0-1 V, 0-3 V or 0-5 V on request
- 4-20 mA
- Low voltage UART (especially for IoT radio modules)

SMT100 Soil Moisture Sensor

SPECIFICATION

Accuracy:	Soil volumetric water content (VWC)
	» Using factory calibration up to $\pm 3\%$ (VWC) in mineral soils with moderate salinity from 0 to 50% VWC
	» Using medium specific calibration up to $\pm 1\%$ (VWC)
	Temperature
	» Typical $\pm 0.2^{\circ}\text{C}$, max. $\pm 0.4^{\circ}\text{C}$ over full range
	» Analog version $\pm 0.8^{\circ}\text{C}$
	Additional output
	» Raw measurement data
	» Dielectric permittivity

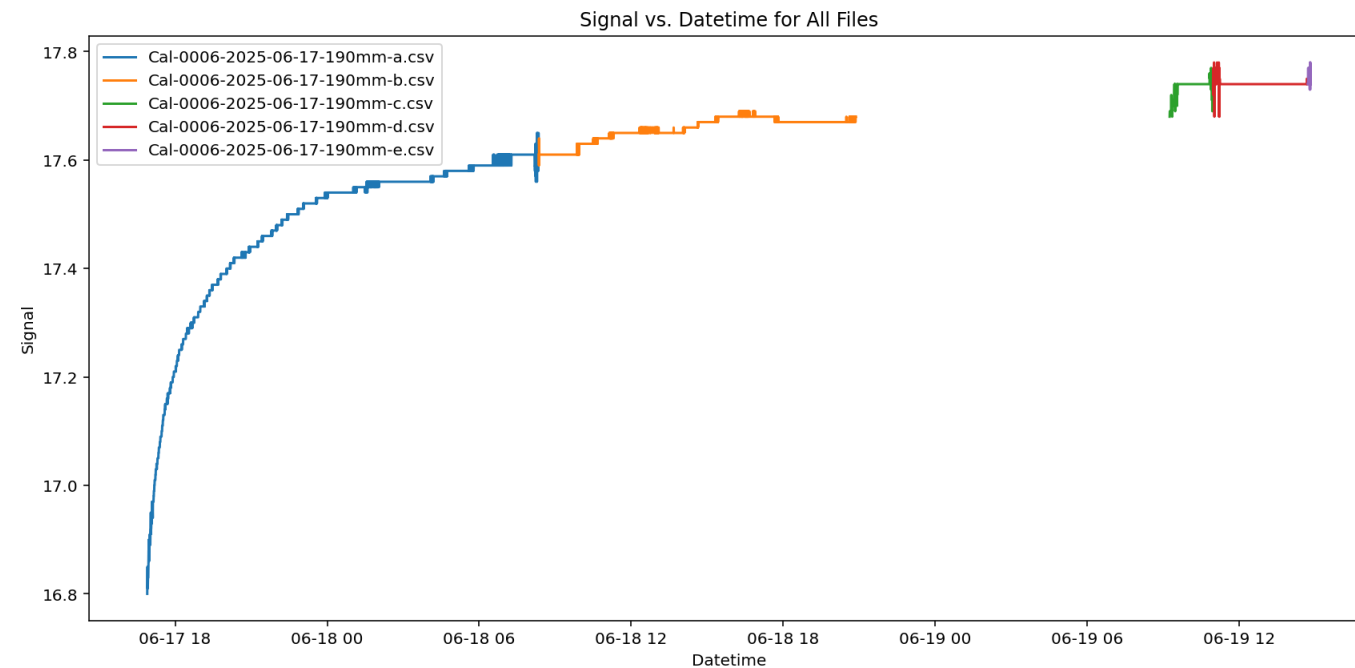
Trubner SMT100

- Comparison with primary reference



Trubner SMT100

- Stabilization
- Signal = % VWC



Calibration: Setup & Sample material

- Setup
 1. Reference = DTI primary setup
 2. Sensor = SMT100
 3. Sample material = inorganic soil from "Skejby"
- Sample material
 - 1) Pulverized, 2) Sieved, 3) Mixed with water
 - 4) Mixed → homogeneous, 5) Filled in test vessel



Calibration: Reference value

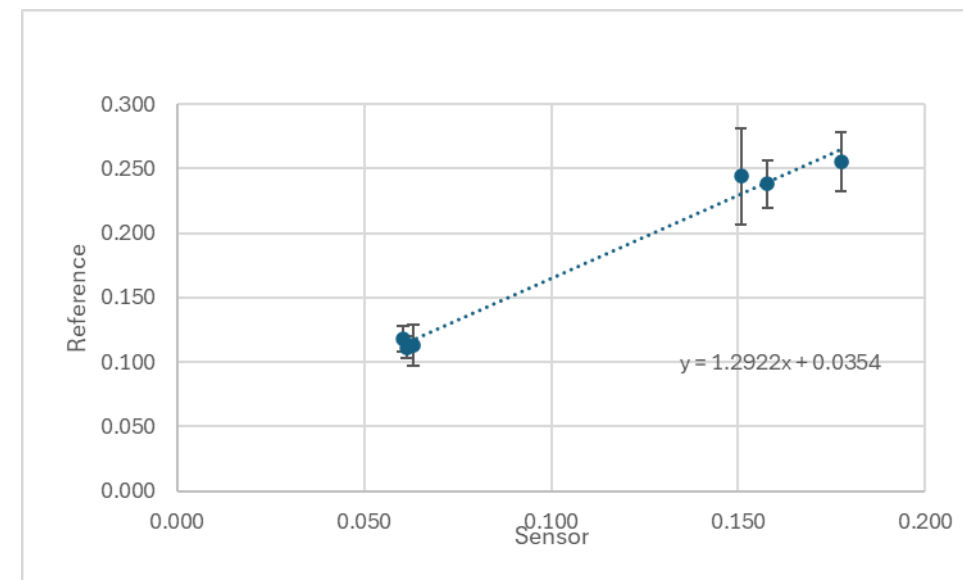
- 4x samples extracted: Volume = 100 cm³
- 1x sample → Reference (primary method)
 - 1) water mass, 2) mass loss → 3) Ratio
- 3x LoD → Mass loss (transfer standard)
 - 3) Mass loss → 4) water mass (using ratio)
- Water density (from temperature)
 - 5) Water volume (4x)
- Sample rings
 - 6) Soil volume (4x)
- Uncertainty
 1. Homogeneity
 2. Soil volume
 3. Reference method



Calibration: Example of result

Truebner SMT100 – Inorganic soil (Skejby)

No	Reference $cm^3 cm^{-3}$	Sensor $cm^3 cm^{-3}$	Error $cm^3 cm^{-3}$	Uncertainty (k=2) $cm^3 cm^{-3}$
1	0.118	0.060	-0.058	0.010
2	0.111	0.061	-0.050	0.008
3	0.113	0.063	-0.050	0.016
4	0.244	0.151	-0.093	0.037
5	0.238	0.158	-0.080	0.019
6	0.256	0.178	-0.078	0.023



Calibration: Next steps

- Calibration in different soil types (DTI)
- Calibration of different sensor types (CMI)
- Calibration of different sensors (TUBITAK)

Questions?



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