Analyzing the reliability of in situ soil moisture measurements for satellite product validation: What makes “fiducial reference measurements” fiducial?

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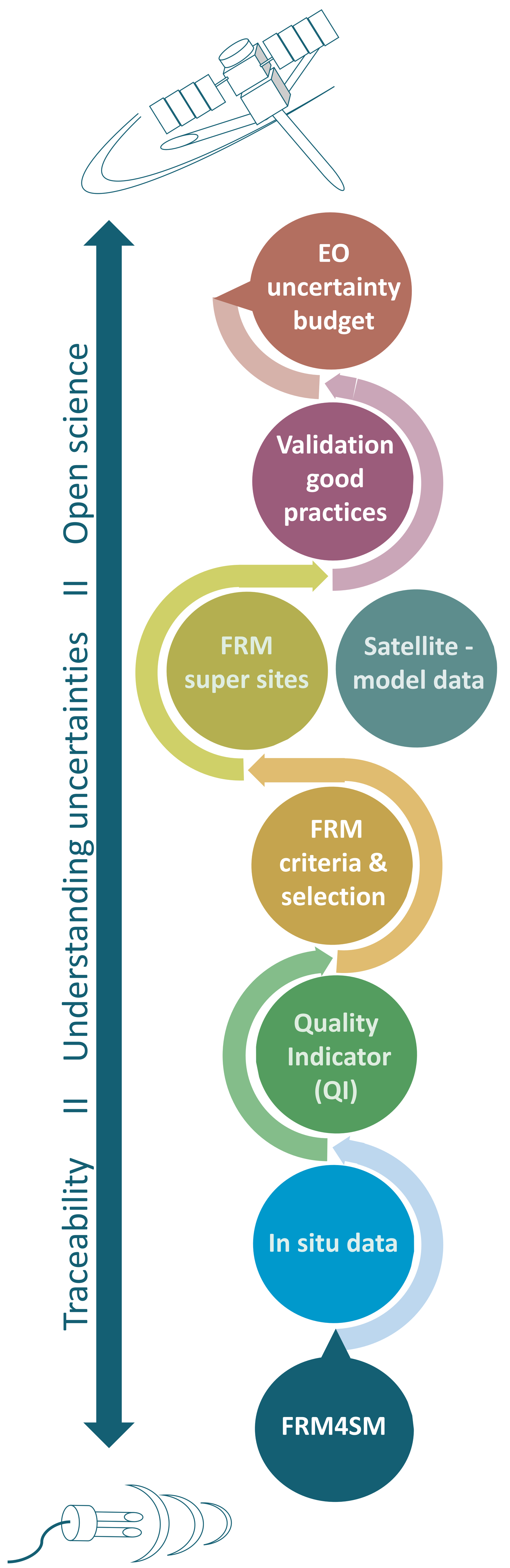
Introduction



What are Fiducial Reference Measurements (FRMs) ?

- Output of satellite communities
- Fully characterized & traceable in situ measurements following community agreed guidelines (GEOS/CEOS QA4EO framework)
- EO data easily & openly accessible
- Data with associated Quality Indicator (QI) → to evaluate its fitness for purpose
- Traceable QIs → internationally agreed reference standards (SI if possible)

ESA’s FRM activities typically comprise activities:

- Establishing ground-based FRM networks for a particular variable
- Specify the protocols and procedures to establish and use such FRM data
- Validate relevant satellite products against established FRM data

Objectives of FRM4SM

FRM4SM targets addressing all the above mentioned goals through:

- Evolution of the International Soil Moisture Network (ISMN): https://ismn.earth
- Evolution of the Quality Assurance for Soil Moisture – free online validation service (QA4SM): https://qa4eo.eu
- Development of a set of in situ soil moisture QIs fully describing uncertainty characteristics
- Development of an “FRM Protocols and Procedures” document – building upon community agreed standards
- Improvement of uncertainty understanding in SSM observations — ISMN/ SMOS validation case studies

→ More info on https://project-frm4sm.geo.tuwien.ac.at/

Project questions & identified issues

(1) What makes “fiducial reference data” fiducial?

(2) Is the creation of a globally-representative FRM subset already feasible for SSM?

(3) What are the current limitations of in situ observations that limit fiduciality?

(4) What is needed to create a full traceability chain from in situ point measurements to the satellite footprint scale?

FRMs ought to be fully characterized and traceable ground measurements to support satellite Cal/Val

Issue 1: Most in situ data providers do not provide any uncertainty information → no calibration standard

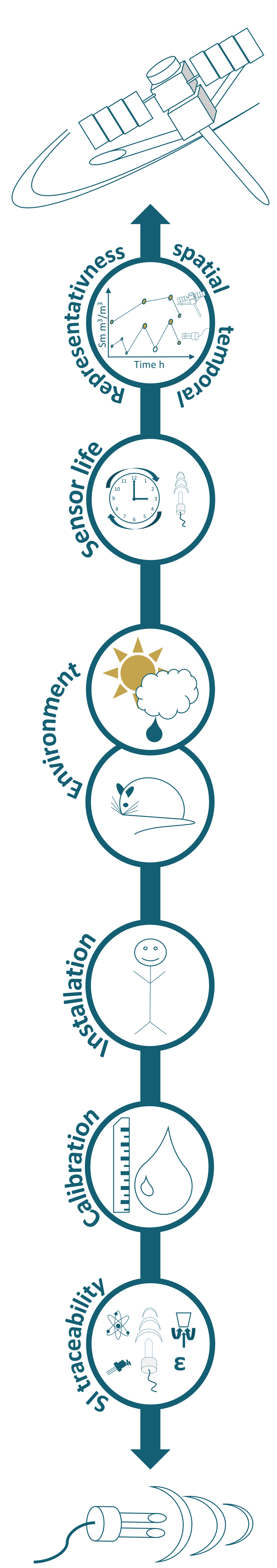
Issue 2: Missing standards to calculate in situ soil moisture uncertainty budget → output FRM4SM data

Issue 3: Upscaling to the satellite scale typically breaks traceability

Issue 4: In situ networks have a strong spatial bias and thus cannot fully capture satellite uncertainty variations

Issue 5: FRMs could differ for individual satellite missions

Uncertainty components & challenges



FRM Qualification for ISMN sensors in top layer:

[5] Gruber et al. 2013

–> Spatial Represstentativness Quality Indicator (QI)

–> Using Triple Collocation (TC) = error estimates for time series

Methodology:

1. Triple Collocation TC (CCI passive, ERA5 land and ISMN)

Tc = in situ error + representativness error

2. Signal to Noise Ratio (SNR)

$$\mathrm{SNR(dB)} = 10\log_{10}\frac{P_s}{P_N}$$

Ps ... Signal
PN ... Error

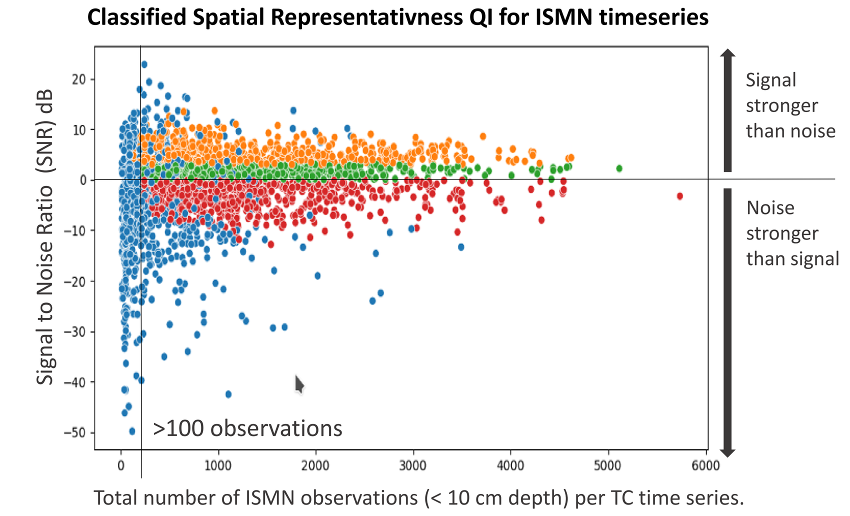
3. Bootstrapping –> Confidence Interval 80%

3. Classification of spatial Representativness QIs for ISMN time series

	Estimated SNR*	QI class
orange	> 3db	Very representative
green	0 – 3 dB	Representative
red	< 0 dB	Not Representative
blue	NaN	Representativness unknown

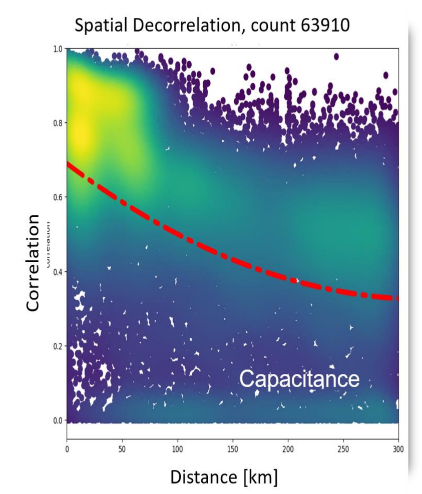
SNR to NaN if: # samples < 100 and CI (80%) > 3 dB

Classified Spatial Representativness QI for ISMN timeseries



Sensor life: Time series buddy check possible?

[6] Dirmeyer et. al 2016



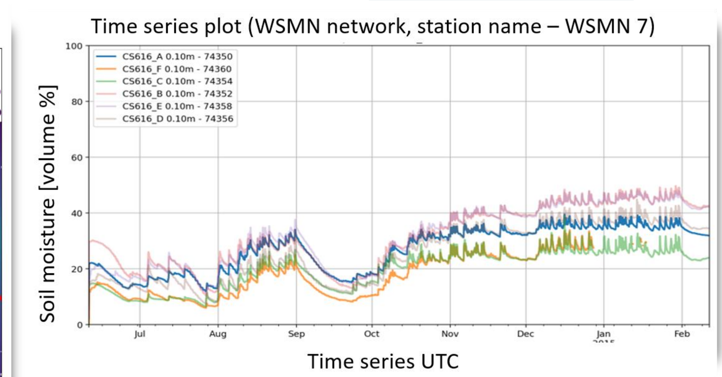


Figure (left): Sensor time series correlation in distance relationship. In this example all capacitance measuring sensors of the ISMN database are investigated. **Figure (right):** Correlation of sensor time series at the same station in the same depth.

–> Investigating neighbouring sensors

- Installation of three sensors per depth for comparison
  - Not easy to understand drift effects
- Comparison of sensors in close proximity – extremely critical (see figure left)
- Sensor life time quite good for at least 10 years (ISMN community)
- Re-calibration of sensors not really done – disturbance of soil

Installation & Environmental factors

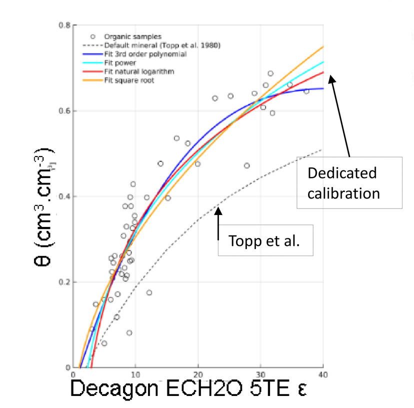
[7] Thorne et al. 2018

–> Sensor loss or resulting poor data quality through problem with contact soil – sensor :

- Incorrect installation (e.g., inexperience, ect.)
- Animals activity (e.g., mice, deer, snails, moles, worms, etc.)
- Harsh environmental conditions (e.g., high latitudes - ice shifts, soil shifts, etc.)
- Heavy weather events (e.g., extreme rain events can flood the sensor, extreme drying events can crack the soil, etc.)
- Agricultural activity (e.g., ploughing the fields, harvesting, etc.)

–> FRM super sites possible across other EO variables

Calibration of soil moisture sensors



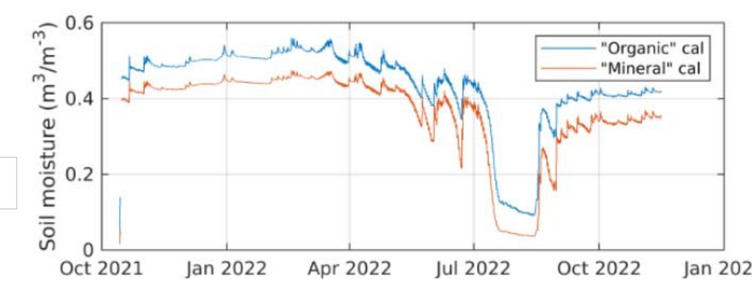


Figure (left): Calibration functions with TOPP et al. 1980 [7] function (mineral soils) in comparison with Bircher et al. 2016 [8] method for high organic soils. **Figure (right):** Differences of quality of soil moisture time series in organic soils when calibrated for TOPP et al. 1980 [7] (mineral) versus Bircher et al. 2016 [8] (organic soils).

–> No calibration standard to this date

- Many functions can be applied e.g., TOPP, CRIM, Mironov, etc.
  - Usually only for mineral soils sometimes high organic soils
  - Measurement highly soil dependent
- Lab calibration usually done with thermo-gravimetric method

[8] Topp et al. 1980 ; [9] Bircher et al. 2016
[10] Roth et al. 1990, [11] Mironov et al. 2004

SI Traceability

–> Diversity of different measuring techniques

–> Uncertainty budget individual per measurement technique

Challenges for traceability chain

–> Scaling differences (in situ versus satellite)

–> No uncertainty/calibration info within ISMN

Establishing traceability

Traceability – uncertainty budget:

1) Identification of influences on in situ soil moisture measurements
2) SI traceability for all soil moisture measurement techniques
3) Generating an uncertainty budget per time series

Traceability – data towards FAIR principles (tracking dataset changes):

1) Versioning of data
2) Persistent Identification (PID) for data (e.g., DOI, hdl, etc.)

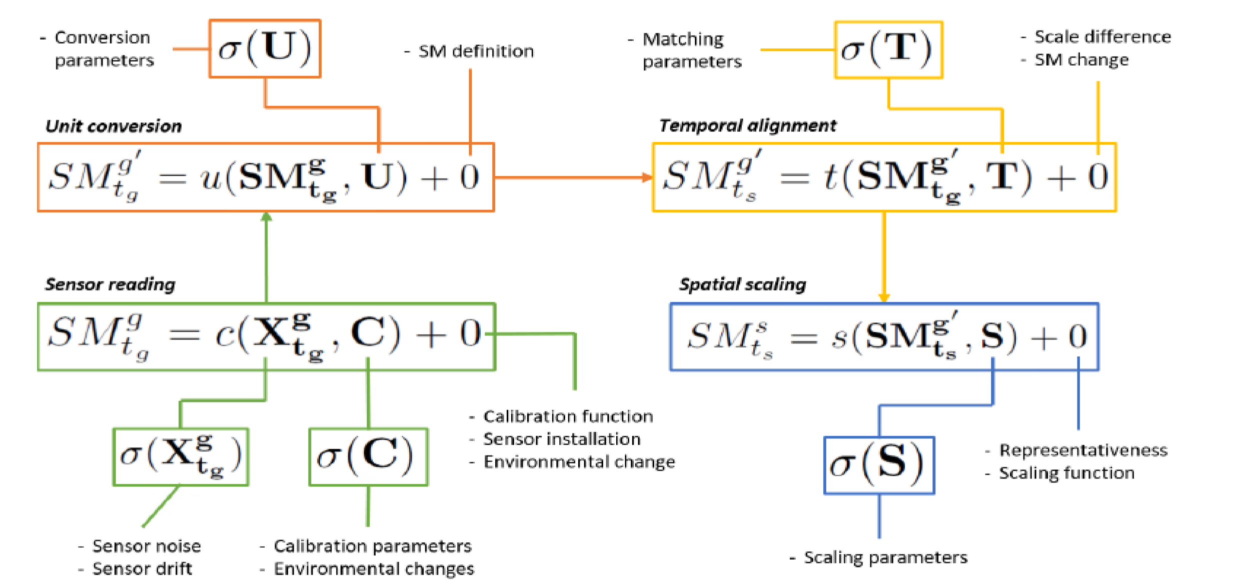
[12] Rauber et al. 2021
[13] FAIR principles
[14] WGDC
[15] Datacite

$SM^{g}_{t_g} = c(\mathbf{X}^{g}_{t_g}, \mathrm{C}) + 0$ ➢ SM(ground scale, ground sampling time, sensor units) ***Sensor reading***

$SM^{g'}_{t_g} = u(\mathbf{SM}^{g}_{t_g}, \mathrm{U}) + 0$ ➢ SM(ground scale, ground sampling time, satellite units) ***Unit conversion***

$SM^{g'}_{t_s} = t(\mathbf{SM}^{g'}_{t_g}, \mathrm{T}) + 0$ ➢ SM(ground scale, satellite overpass time, satellite units) ***Temporal alignment***

$SM^{s}_{t_s} = s(\mathbf{SM}^{g'}_{t_s}, \mathrm{S}) + 0$ ➢ SM(satellite scale, satellite overpass time, satellite units) ***Spatial scaling***



Effect	Type	Correlated	Magnitude	Confidence
Sensor noise	R	N		
Sensor drift	S	N		
Calibration parameters	S	P		
Calibration function	S	P		
Sensor installation	S	P		
Environmental factors	R+S	P		
Conversion parameters	S	P		
SM definition	S	P		
Matching parameters	S	P		
Scale difference	R+S	P		
SM decorrelation	R+S	P		
Scaling parameters	R+S	P		
Spatial representativeness	R+S	P		
Scaling function	R+S	P		

Equation and Figure (top): The equation shows the different currently identified uncertainty sources which are then included in the traceability Diagram figure below. The + 0 = no uncertainty attached (assumption).

Table (left): This table shows the effects table for all currently identified uncertainty factors and tries to list the differences of theses errors: R = Random, S = Systematic; Correlated: Y = Yes, N = No, P = Potentially; 1 = Estimates only; 2: Some analysis performed to evaluate; 3: Rigorous analysis performed. Magnitudes are given in m3 / m3.

Key message / future direction

–> Important to find all uncertainty influences

–> Calculation of uncertainty budget

- Important to understand current limitations
- Finding a way to quantify uncertainty associated with
  - (lacking) calibration
  - Installation & environmental factors
- Working more interdisciplinary

–> Clear understanding what is really needed for soil moisture satellite validation

- How does a best possible data quality look like (= FRM4SM subset of data)
- Finding common ground and differences per satellite mission
- FRM(4SM) super sites

–> Building upon and towards community agreed standards

- Data sharing towards open source and FAIR principles
- Best practices and recommendations for best possible FRM4SM data

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Sharing is encouraged