Why does my soil moisture sensor read negative?

Improving accuracy of dielectric soil moisture sensors

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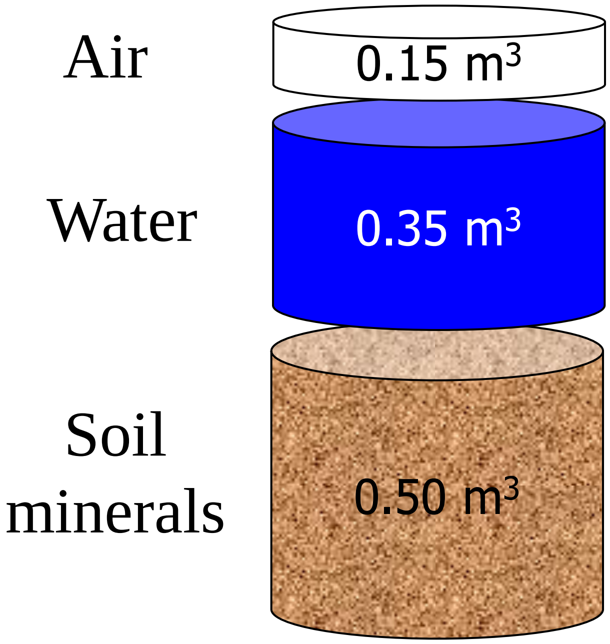
Outline

- Introduction
  - VWC definition
  - Direct vs. indirect measurement methods
  - Dielectric permittivity for measuring VWC
- Accuracy
  - Definitions and scope
  - Approach to accuracy analysis (mixing model)
- Sensor (dielectric permittivity) accuracy
- Converting dielectric permittivity to VWC
- Installation quality and techniques

Volumetric water content



- Volumetric Water Content (VWC): Symbol – θ
- V_{water}/V_{soil}

θ = 0.35 m³ water / 1 m³ total soil volume

= 0.35 m^3/m^3 or 35% VWC

Measurement techniques

- Direct measurements
  - Directly measure the property
  - e.g. length with calipers

- Indirect measurements
  - Measure another property and relate it to the property of interest through a calibration
  - e.g. expansion of liquid in a tube to determine temperature

Direct measurement of VWC

- Volumetric water content (θ)
  - Obtain moist soil sample with *known volume*
  - Weigh moist sample
  - Dry sample at 105° C for 24 h
  - Weigh dry sample

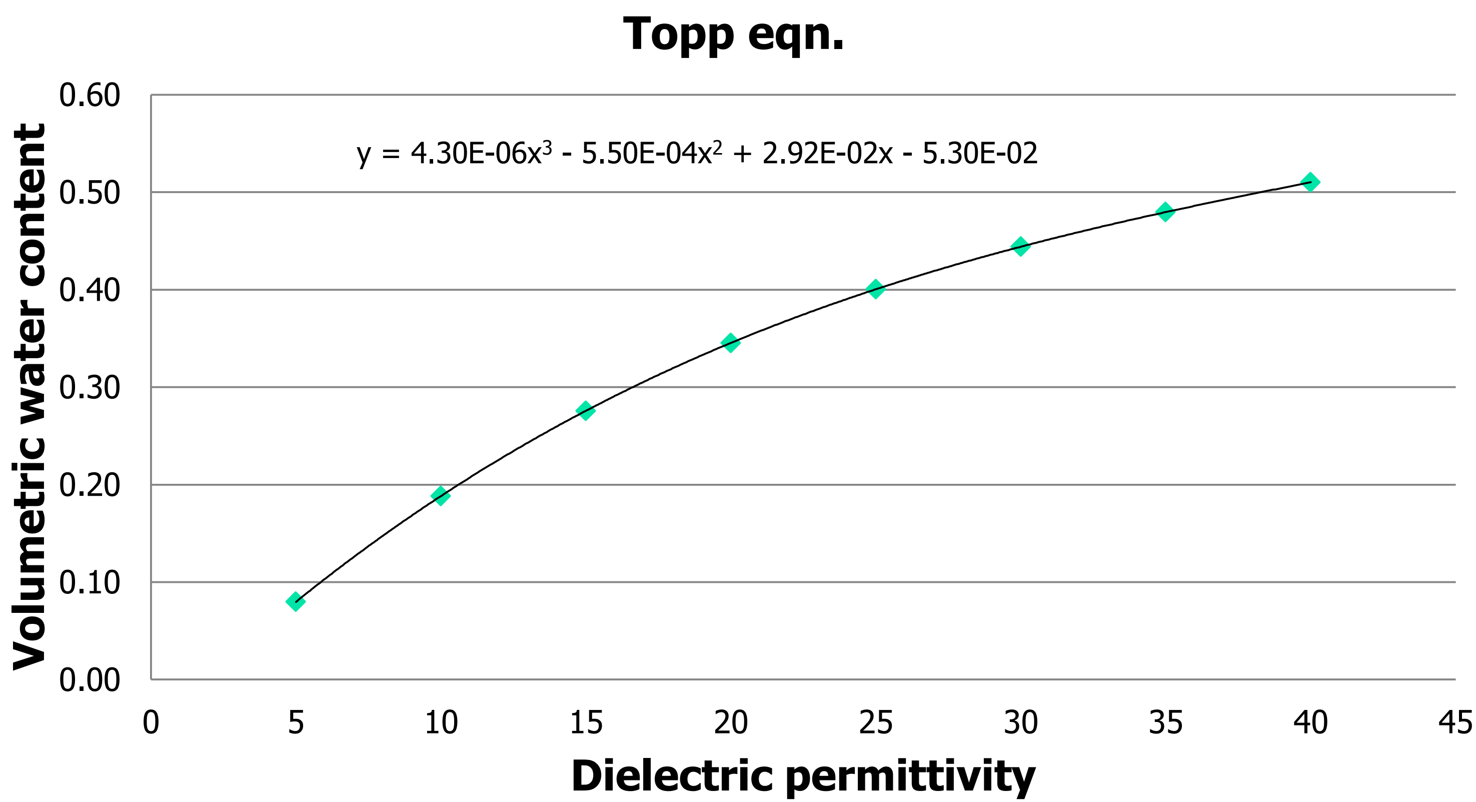
$$\theta = \frac{M_{moist} - M_{dry}}{V_{sample}}$$

Dielectric theory: How it works

- In a heterogeneous medium:
  - Volume fraction of any constituent affects total (bulk) dielectric permittivity
  - Changing any constituent volume changes the total dielectric
  - Changes in water volume have the most significant effect on the total dielectric

Material	Dielectric Permittivity
Air	1
Soil Minerals	3 - 16
Organic Matter	2 - 5
Ice	5
Water	80

Relating dielectric permittivity to VWC



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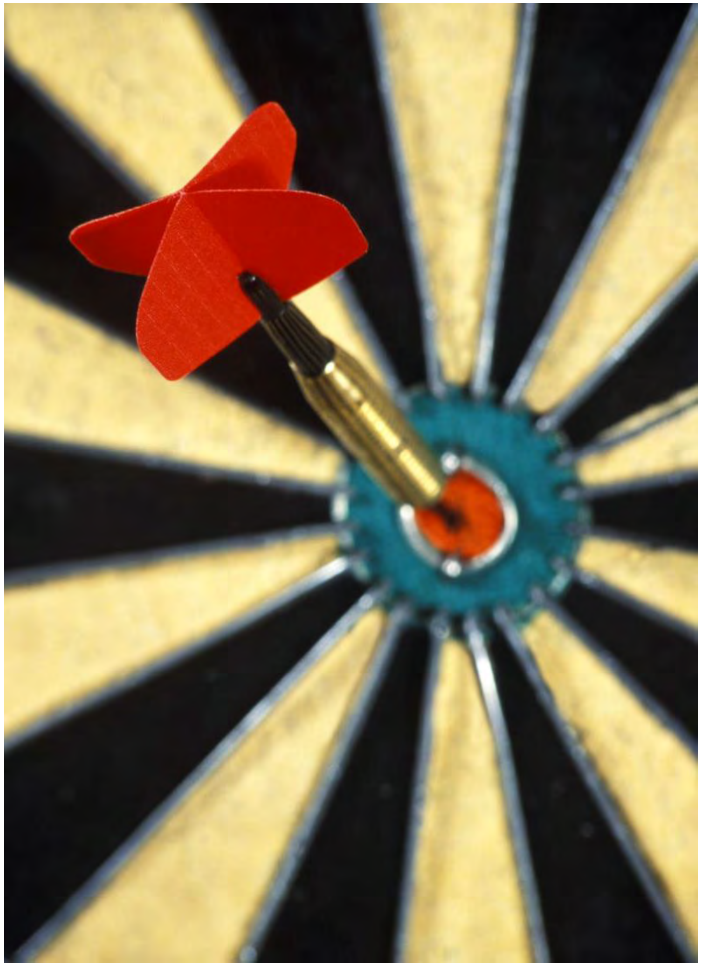
Accuracy

- **Resolution** - The smallest change that can be detected
- **Precision** - The degree of reproducibility of measurement
- **Accuracy** - How close the measured value is to the actual (absolute) value

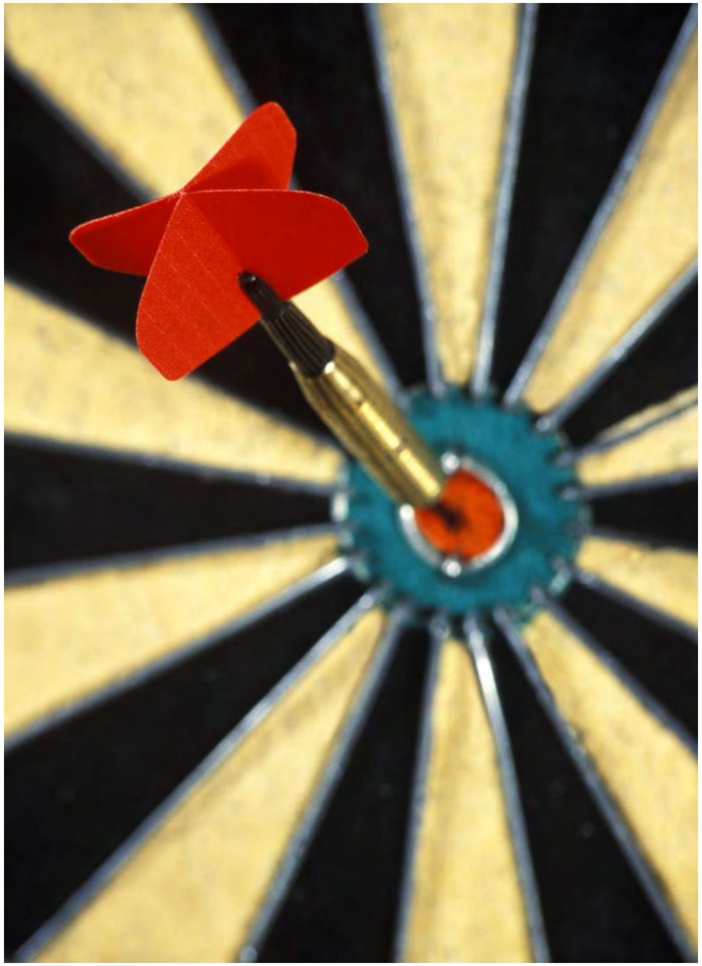


Accuracy (of what measurement?)

- What does it mean?
  - Dielectric permittivity accuracy?
  - **VWC** accuracy

Questions:

- Why might a sensor read a negative VWC?
- Can a sensor really have 1-2% VWC accuracy for all soils?



Approach to accuracy analysis

- Use generalized dielectric mixing model
- Set default mixing model parameters to realistic values
- Vary model parameters over normal values and see how they affect measured VWC

Generalized dielectric mixing model

$$e_b^a = x_a e_a^a + x_m e_m^a + q e_w^a$$

- ε is the apparent dielectric permittivity.
- *x* is the volume fraction.
- The subscripts *b, a, m,* and *w* refer to bulk, air, mineral and water

Generalized dielectric mixing model

By rearranging, we can get an equation relating θ to:

- ε_b Bulk soil permittivity (sensor accuracy)
- ρ_b Bulk density of soil
- ε_m Permittivity of minerals
- ρ_s Particle density
- ε_w Permittivity of water

$$q = \frac{e_b^a + (1 - e_m^a)\dfrac{r_b}{r_s} - 1}{e_w^a - 1}$$

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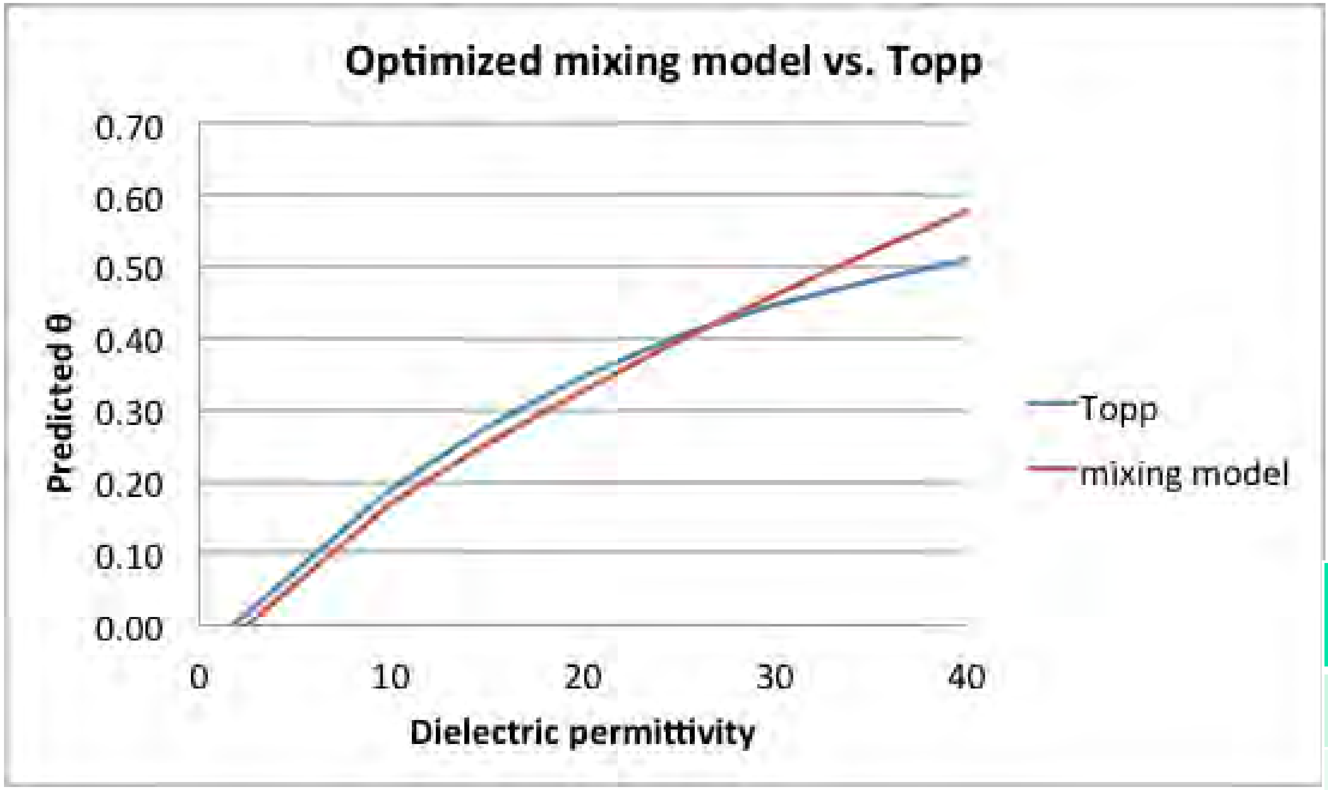
Mixing model default parameters



Mixing model parameter	Value
α	0.65
ε_{air}	1
$\varepsilon_{mineral}$	4
ε_{water}	78.5
ρ_b	1.4 g/cm^3
$\rho_{mineral}$	2.65 g/cm^3

Factors affecting VWC accuracy

1. Sensor's ability to measure dielectric permittivity accurately (sensor accuracy)

2. Relationship between dielectric permittivity and VWC

3. Installation quality

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Sensor accuracy

- Accuracy with which sensor measures *dielectric permittivity*
- This is the **ONLY** specification that the sensor manufacturer can give







Sensor accuracy:
Sensor-sensor repeatability

- Manufacturer must control processes so that all sensors read the same
  - EC-5
- Some sensors are calibrated against dielectric permittivity standards to improve repeatability
  - Calibration drives up cost
  - 5TE, 5TM, 10TM, GS3, RS3

Sensor Accuracy:
Electrical conductivity (salt) effects

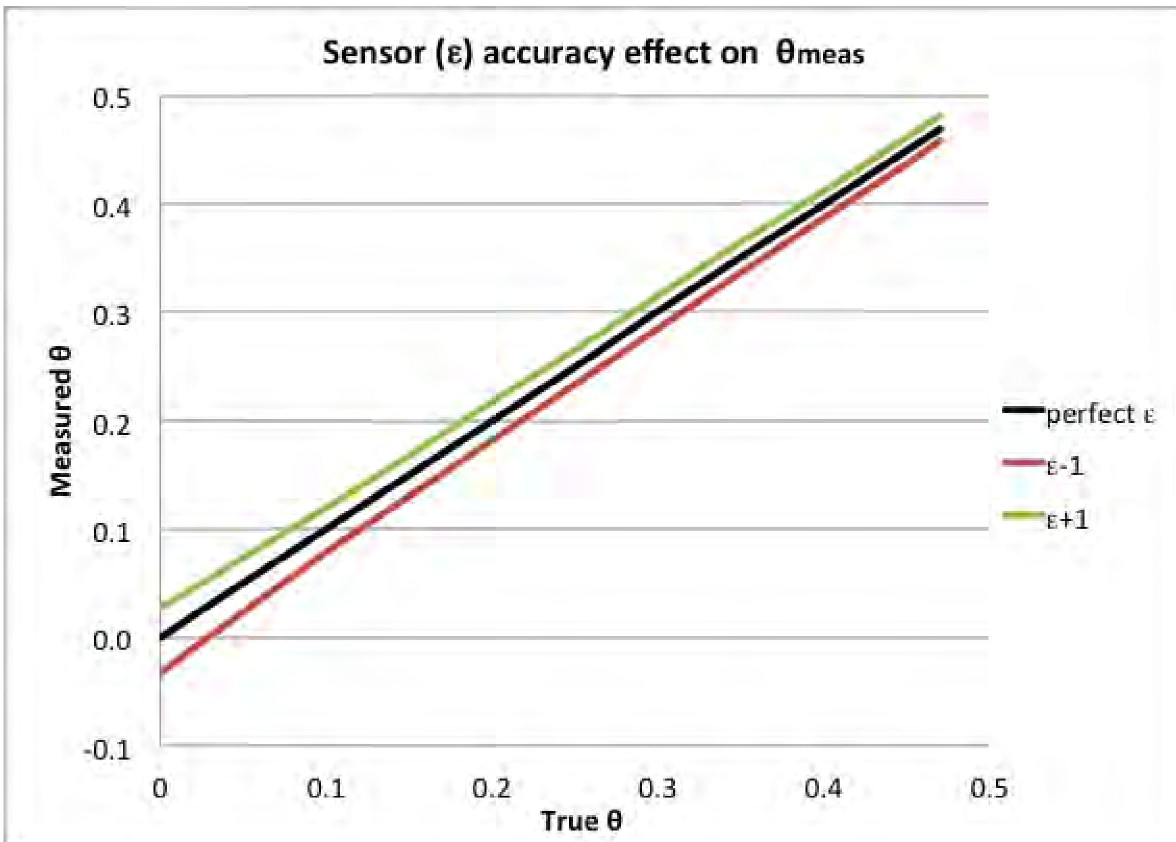
- Depends on the ability of the sensor to separate real (capacitive) and imaginary (conductive) components of dielectric permittivity
- Low frequency sensors, such as the discontinued EC-10 and EC-20 (5 MHz) have high sensitivity to salts
- With new higher frequency sensors (70-100 MHz), effects are small except in saline soils

Sensor Accuracy:
Temperature effects

- Sensor electronics must have negligible inherent temperature sensitivity
- Permittivity of water is temperature dependent (negative correlation)
- Electrical conductivity of soil solution is highly temperature dependent (positive correlation)
- Impossible to compensate in electronics
- Must do correction during data analysis

Sensor (ε) accuracy effect on θ_{meas} accuracy

- Sensor accuracy spec for Decagon sensors: ±1 ε (unitless) from ε = 1 to 40
- Resulting error ±0.03 m^3/m^3 at dry end to ±0.01 m^3/m^3 at wet end



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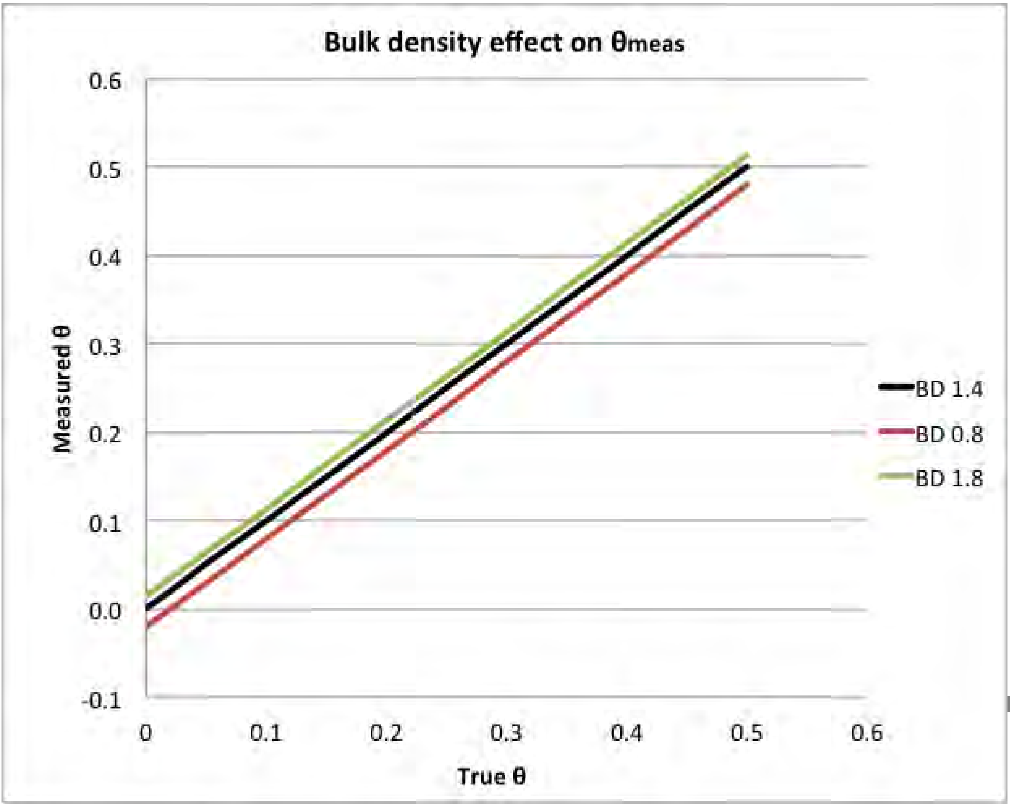
Converting dielectric permittivity to VWC

- Commonly called a calibration equation
- Each soil has a different relationship
  - Most mineral soils have similar relationship
  - Relationship generally determined empirically
  - Topp equation used extensively
- Sensor manufacturer cannot control or specify this relationship

Errors from ε to θ_{meas} conversion
Effect of bulk density on accuracy

- Bulk density of soils varies widely
  - Agricultural soils can range from 0.8 to 1.8 g/cm^3
  - This represents ±2% VWC error
  - In organic, volcanic, or compacted soils the error can be much larger

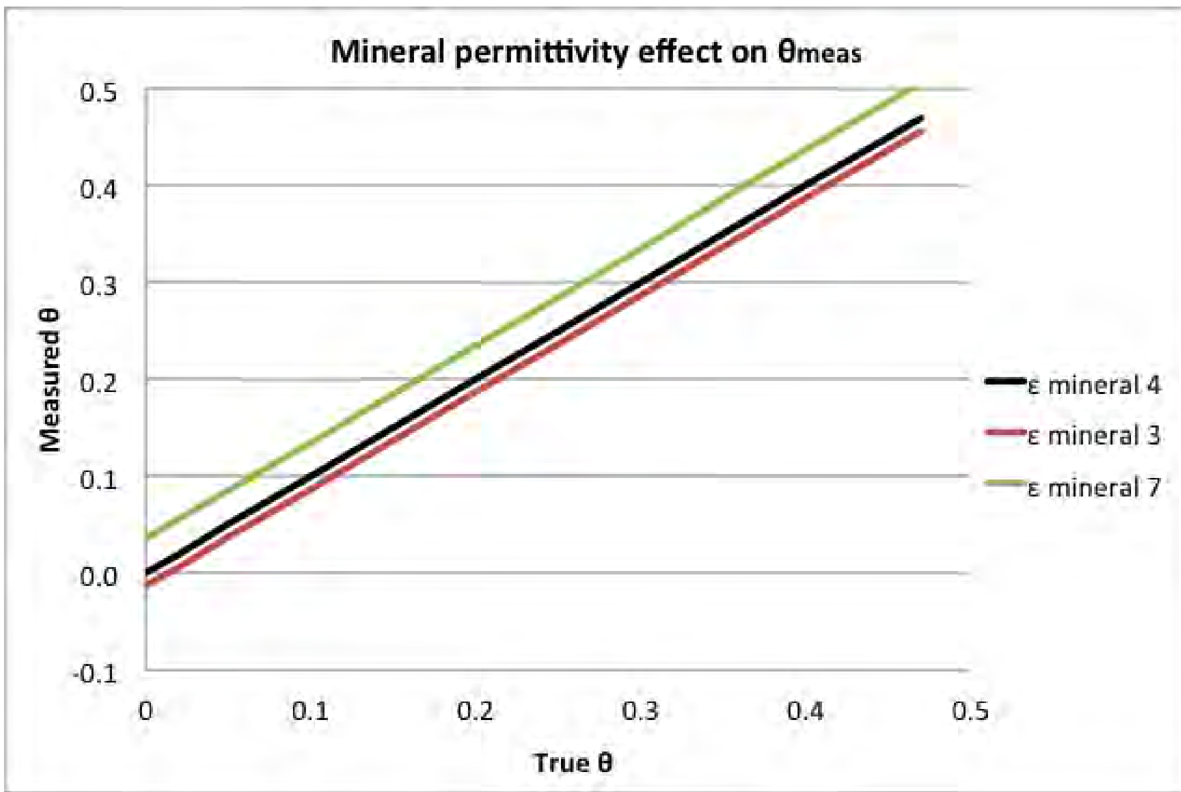


Mixing model parameter	Value
α	0.65
ε_{air}	1
$\varepsilon_{mineral}$	4
ε_{water}	78.5
ρ_b	0.8 to 1.8 g/cm^3
$\rho_{mineral}$	2.65 g/cm^3

Errors from ε to θ_{meas} conversion

Effect of mineral permittivity on accuracy

- Dielectric permittivity of minerals *typically* 3-7
  - This represents ±2.5% VWC error
  - Titanium minerals can have permittivity of over 100!

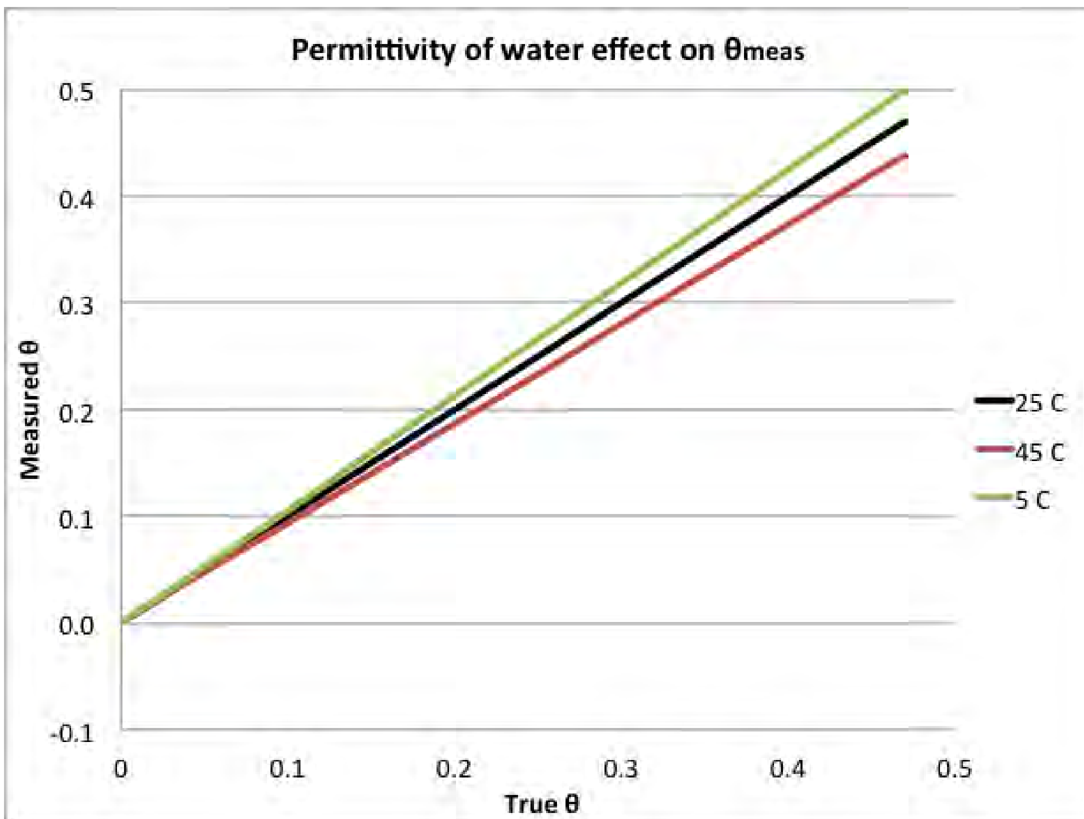


Mixing model parameter	Value
α	0.65
ε_{air}	1
$\varepsilon_{mineral}$	3 - 7
ε_{water}	78.5
ρ_b	1.4 g/cm^3
$\rho_{mineral}$	2.65 g/cm^3

Errors from ε to θ_{meas} conversion

Effect of permittivity of water on accuracy

- Dielectric Permittivity ~80 at room temperature.
  - The dielectric decreases with increasing temperature at about 0.5%/°C
  - Error 0 in dry soil to ±0.03 m^3/m^3 in wet soil



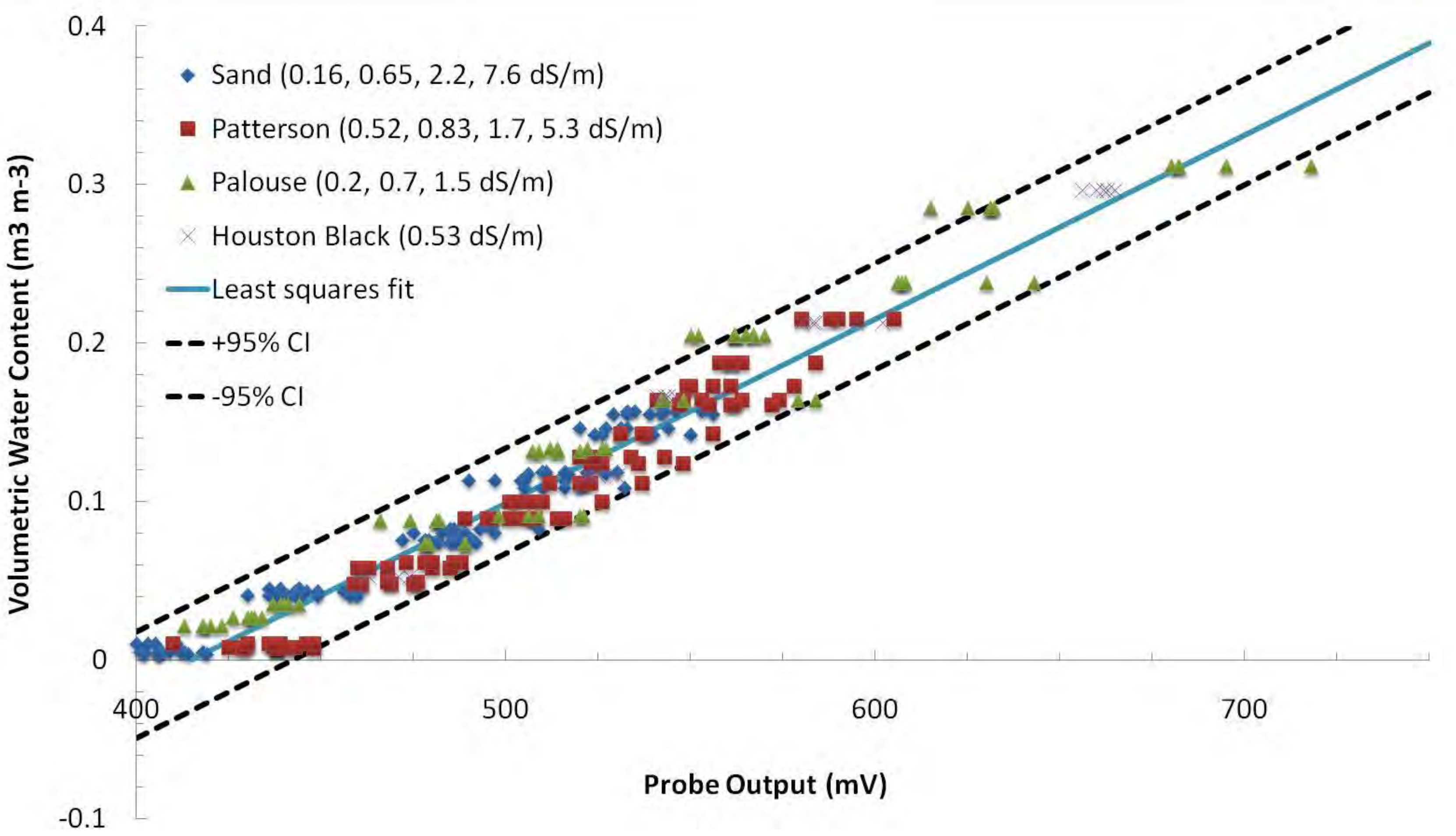
Mixing model parameter	Value
α	0.65
ε_{air}	1
$\varepsilon_{mineral}$	4
ε_{water}	71 – 85 (45 to 5 °C)
ρ_b	1.4 g/cm^3
$\rho_{mineral}$	2.65 g/cm^3

Accuracy of permittivity/VWC relationship

Effect of dielectric permittivity of water (continued)

- Water that is "bound" to particles or organic matter has lower apparent permittivity than "free" water
  - Largest error in clay soils or high organic soils
  - Higher frequency dielectric sensors (TDR, TDT) more significantly affected
  - Capacitance or frequency domain sensors generally not affected

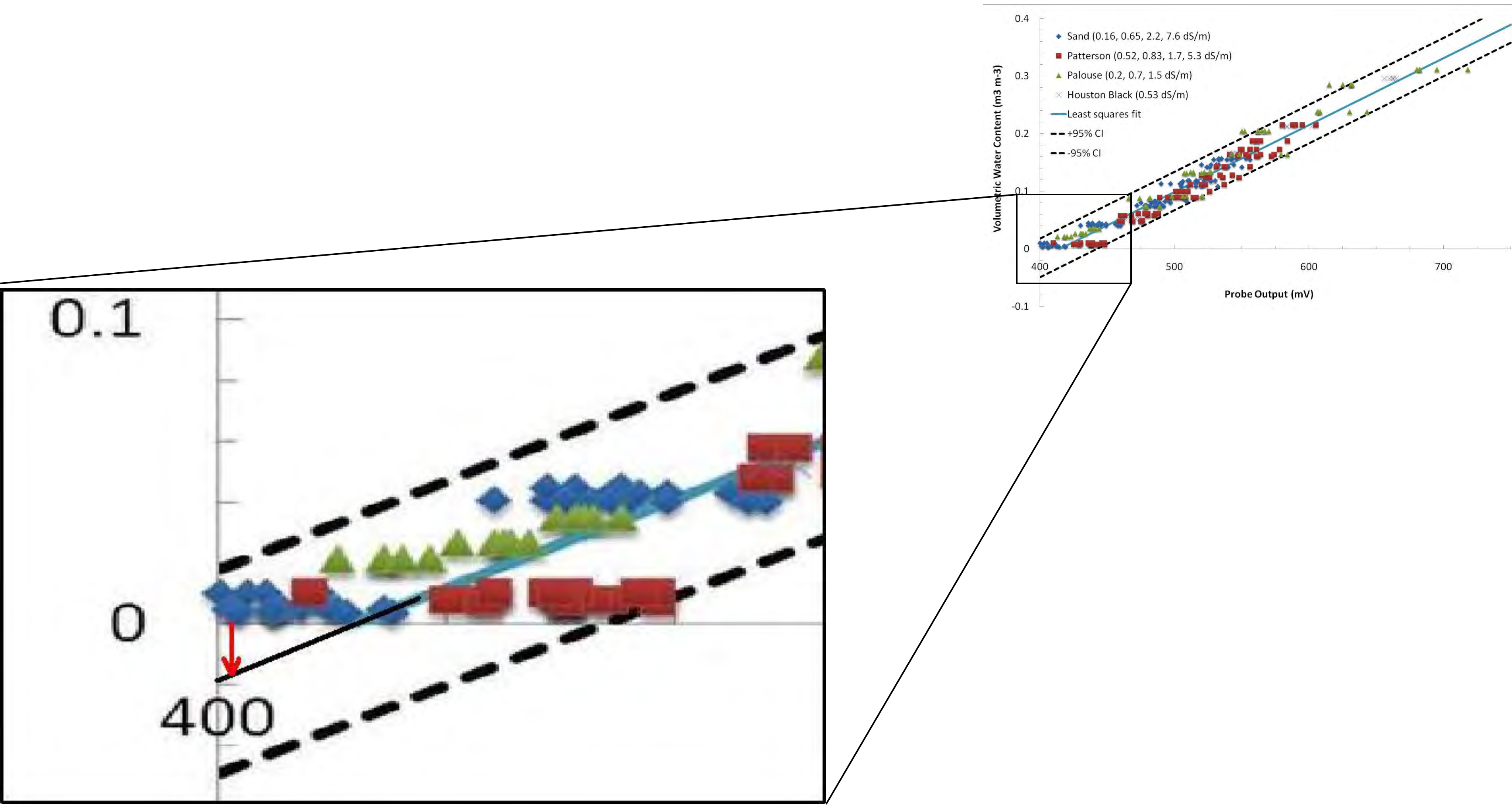
Generic calibrations
What we typically expect in mineral soil



Kizito et. al (2008)

Why do my sensors read negative?

Generic calibration doesn't match your soil



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Kizito et. al (2008)

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Generic calibrations **fail** when:

- Your soils are not "typical" soils
  - Organic soils
  - Volcanic soils
  - Odd mineralogy (e.g. titanium) soils
  - Abnormally high EC soils
  - Non-soil media (potting soil, peat, rockwool, perlite, cocus, etc.)

- Your study requires better than about 0.03 m^3/m^3 accuracy

Soil-specific calibrations

- Several methods are commonly tried
- Some produce good results, some don't
  - Dry down method (and modifications of this method)
  - Homogenized soil calibration

Soil-specific calibrations
Dry down method

- Sensors are placed in saturated soil in a large container
- Container is weighed to calculate actual volumetric water content
- "Actual volumetric water content" is correlated with sensor output

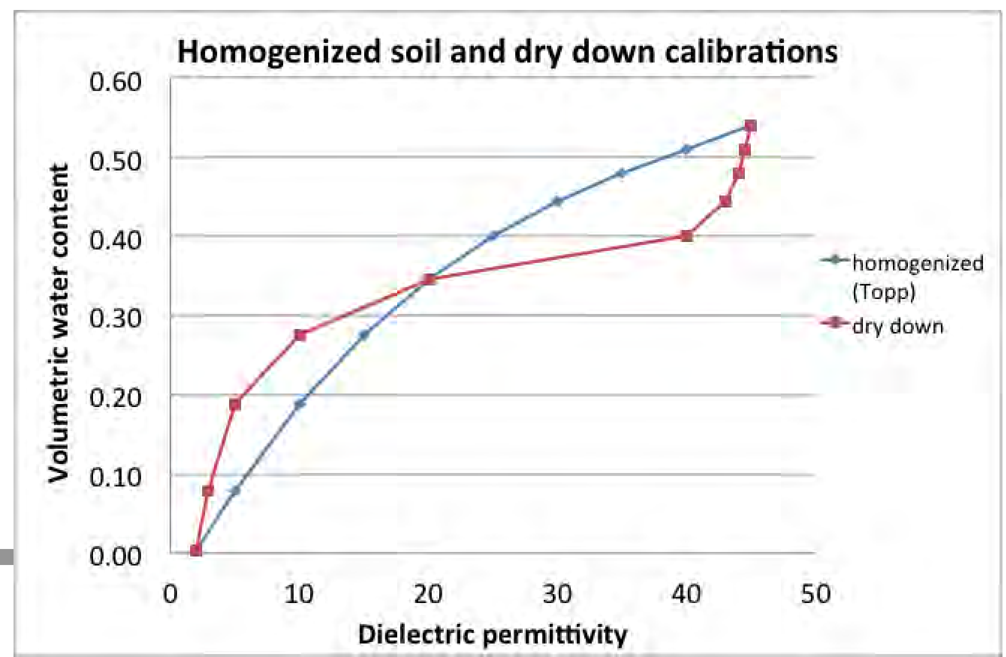
Soil-specific calibrations
Dry down method

Benefits

- Appears to mimic environmental conditions
- Soil disturbance is minimized

Limitations

- Results highly dependent upon where the sensor is within the container (drying front)
- Drying can take weeks
- Almost never gives good results



Soil-specific calibrations
Homogenized soil method (recommended)

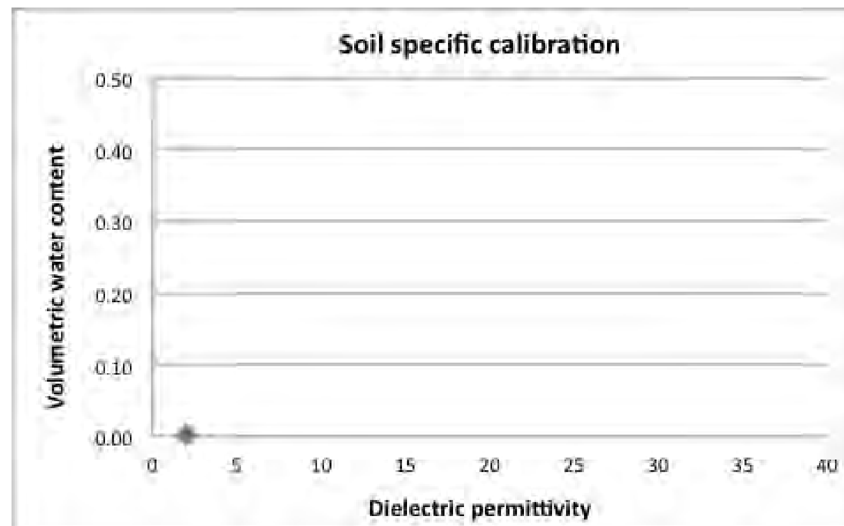
- Air dry and sieve soil
- Pack dry soil to desired bulk density

Soil-specific calibrations
Homogenized soil method (recommended)

- Carefully insert sensor and record output (multiple times)

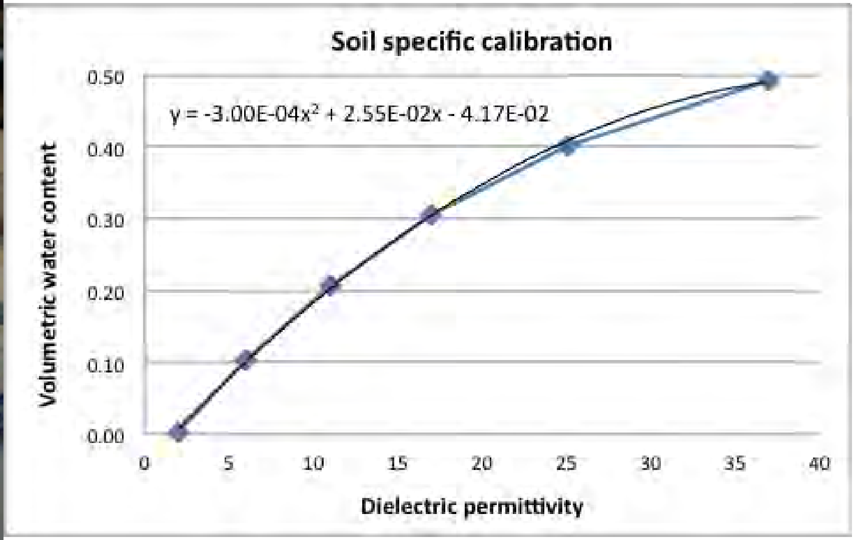
Soil-specific calibrations
Homogenized soil method (recommended)

- Collect known volume(s) of soil to obtain true (absolute) VWC by oven drying



Soil-specific calibrations
Homogenized soil method (recommended)

- Add enough water to increase VWC by about 0.1 m^3/m^3 and thoroughly homogenize
- Repeat



Soil-specific calibrations
Homogenized soil method

Benefits

- Homogenized soil prevents VWC heterogeneity in sample
- Volumetric sub-samples give true VWC by direct oven drying method
- No specialized equipment needed

Limitations

- Disturbed soil sample
- Bulk density hard to control as water is added to soil
- Volumetric sub-samples impossible to collect in some materials

Soil-specific calibrations
Homogenized soil method

- We highly recommend the homogenized method to customers
  - Step-by-step instructions at www.Decagon.com
  - Calibration service offered (hundreds of soils/non-soil media calibrated)

- With care, should be able to get VWC accuracy to ±0.01 to 0.02 m^3/m^3

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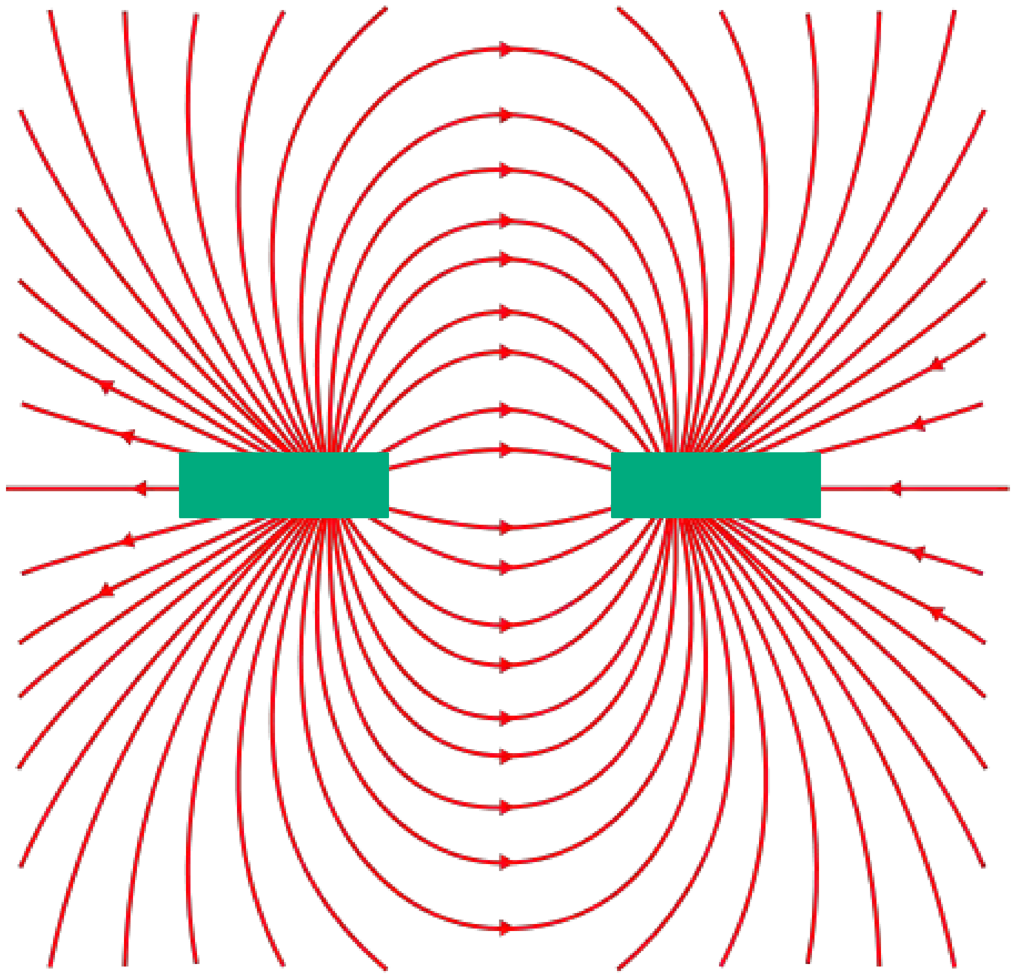
Installation quality

The single largest source of error in measured VWC is poor installation!

Installation – sensitivity of measurement



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Installation quality
Voids

- Typically occur near sensor where sensitivity is greatest
  - VWC underestimated
  - ***Often results in negative VWC measurement***
    - Error can be 0.1 m^3/m^3 or more

Installation quality
Bulk density

- Earlier analysis showed effect of bulk density on measured dielectric/VWC
- Disturbed or repacked soil often has different bulk density

Insert sensor into undisturbed soil

Proper installation
Sidewall

- Dig trench to desired depth
- Carefully insert sensor into undisturbed side wall
- Backfill trench at native bulk density

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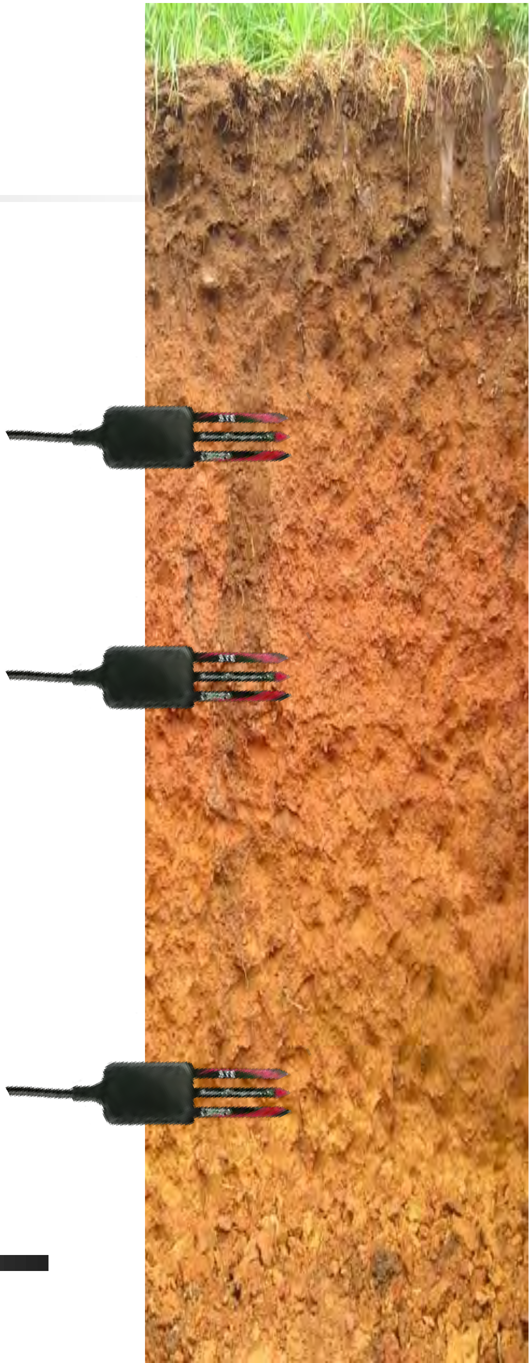
Proper installation
Sidewall

Advantages

- Visual and tactile confirmation of quality insertion
- Undisturbed soil above sensor
- Horizontal insertion measures VWC at discrete depth
- Common and accepted method



Disadvantages

- Large excavation (effort)
- Large scale soil disturbance

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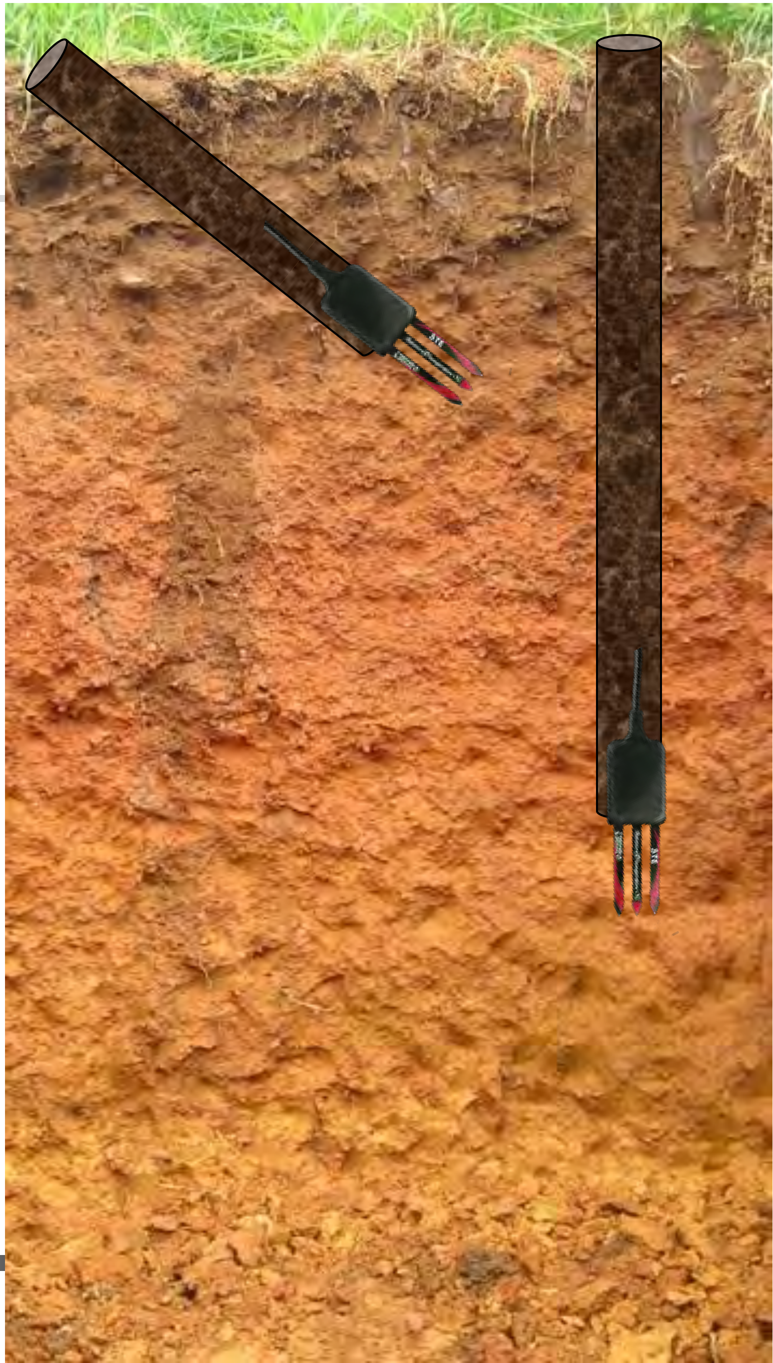
Proper installation
Down hole

- Auger hole to desired depth
  - Often 45° angle
- Insert sensor into undisturbed soil in bottom of hole
- Carefully backfill hole at native bulk density



Proper installation
Down hole

Advantages

- Deep installations possible
- Minimal soil disturbance

Disadvantages

- Impossible to verify quality installation
- One hole per sensor
- Installation tool necessary

Installation
Hard or stony soils

- Hard soils
  - Use tool to make pilot hole
  - Must be slightly smaller than sensor
- Stony soils
  - Sieve stones from a volume of soil
  - Re-pack sieved soil around sensor
    - Disturbed sample
    - Possible poor accuracy
    - Still measures dynamics well

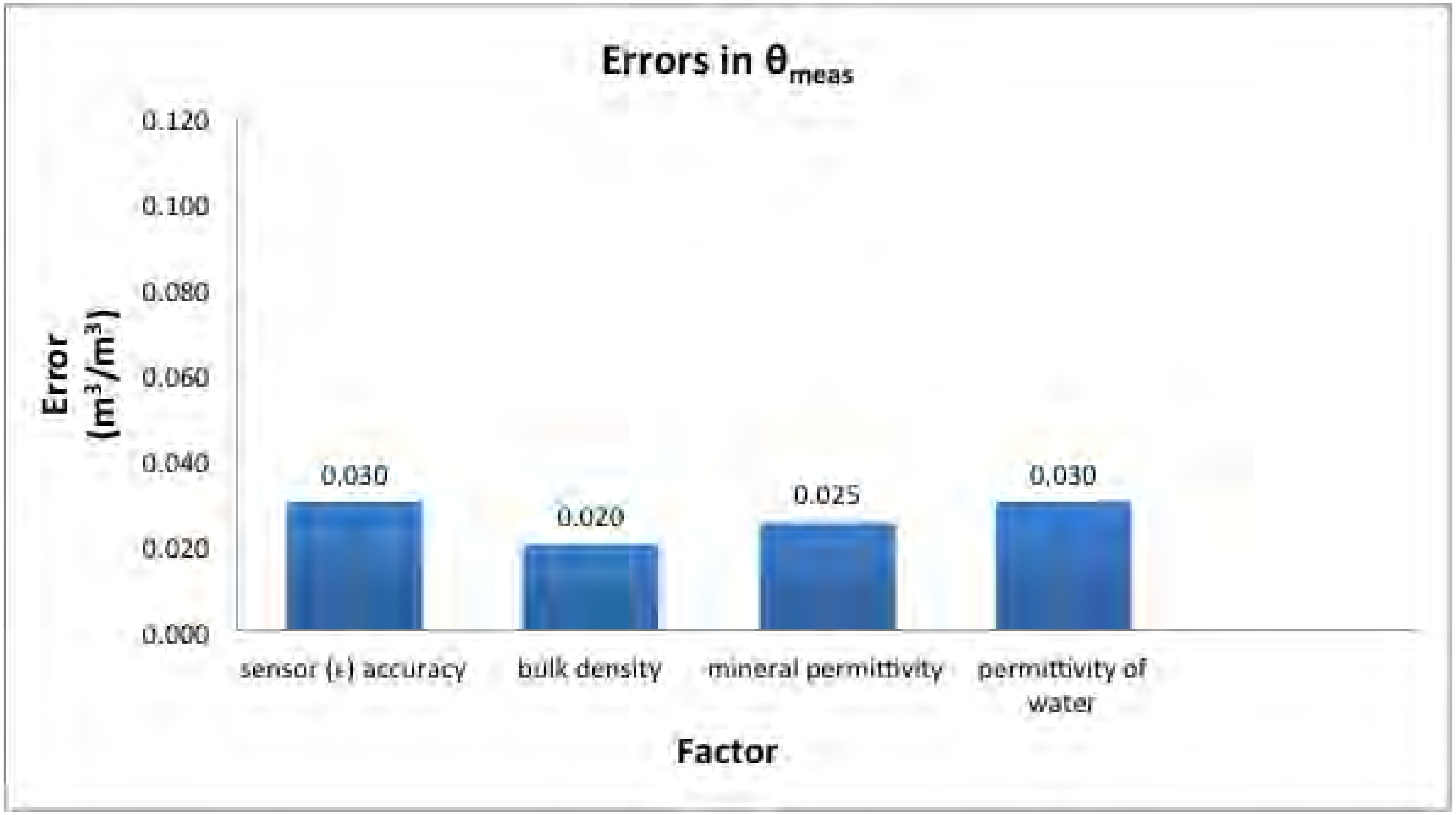
4th source of error – point vs. field scale
(I know I said I was only going to talk about 3)

- All dielectric sensors have small measurement volume (10's to 100's of cm^3)
- Scaling point measurements to representative field scale measurement is difficult
  - Replicated measurements and averaging
  - Other strategies available
  - Whole topic is outside the scope of this discussion

Take-home points

- 3 sources of error in VWC measurement
  - Sensor error
    - How accurately the sensor measures dielectric permittivity
    - Only factor that can be controlled by manufacturer
  - Dielectric permittivity to VWC conversion
    - Depends on bulk density, temperature, mineralogy
    - Generic calibrations work for most "typical" soils
    - Soil-specific calibration necessary in some cases

Take-home points



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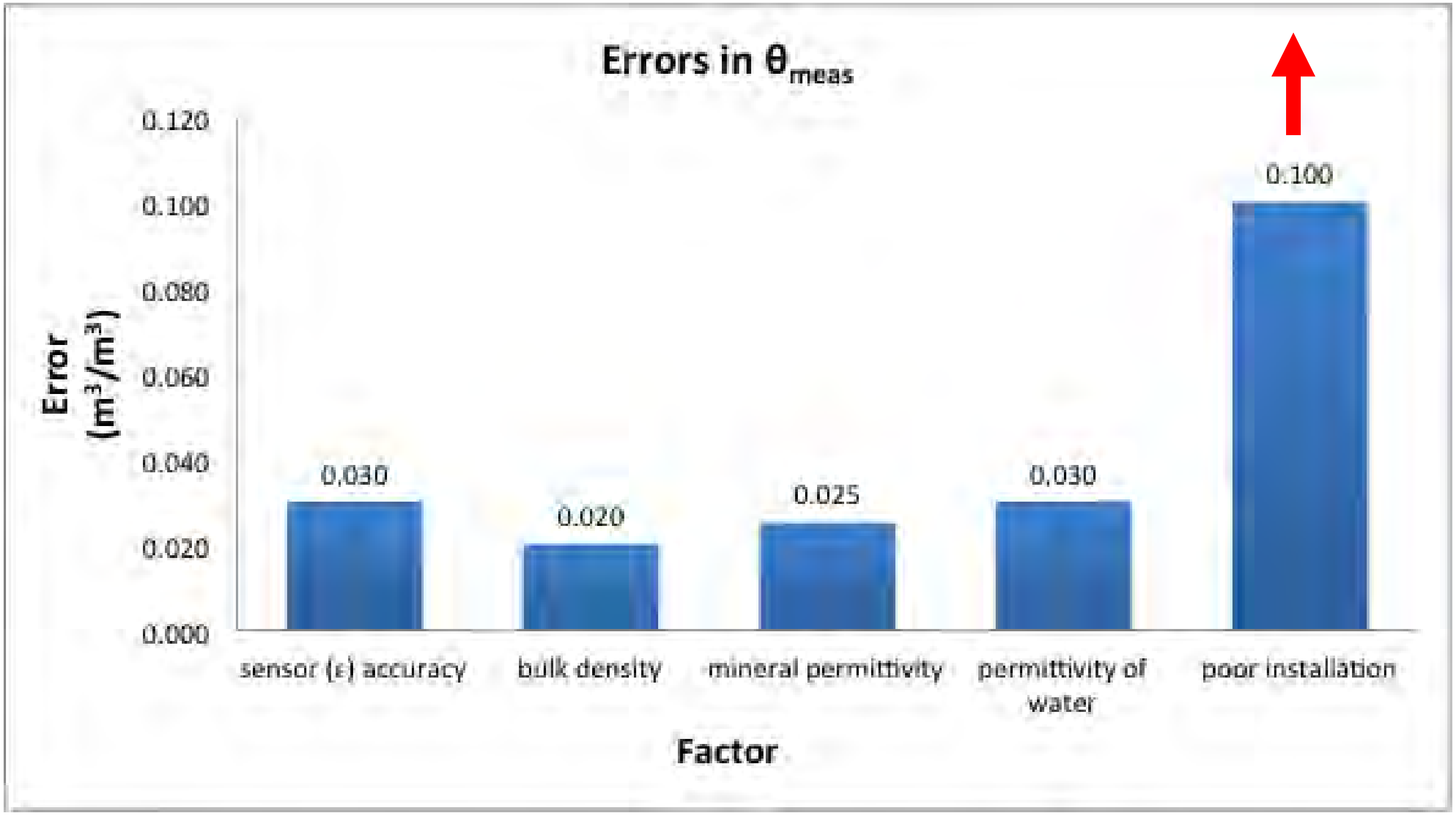

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