Why does my soil moisture sensor read negative?

Improving accuracy of dielectric soil moisture sensors

Douglas R. Cobos, Ph.D.

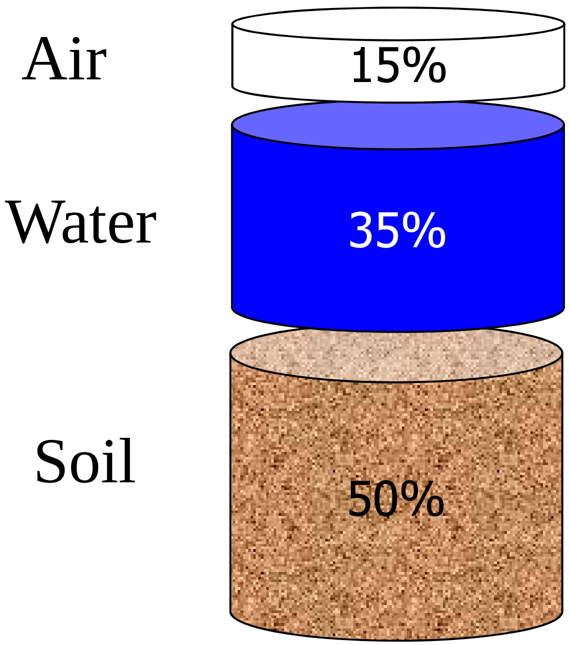
Decagon Devices and

Washington State University

Outline

- Introduction
  - VWC
  - Direct vs. Indirect measurement methods
  - Dielectric permittivity for measuring VWC
- Accuracy
  - Definitions and scope
  - Sensor (dielectric) accuracy
    - Repeatability
    - Electrical conductivity effects
    - Temperature effects
  - Converting dielectric permittivity to VWC
    - Dielectric mixing model
    - Factors affections permittivity to VWC relationship
    - Soil specific calibrations
  - Installation quality
    - Sidewall installations
    - Down hole installations
    - Hard and stony soils

Volumetric water content



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

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^{o} C for 24 h
  - Weigh dry sample

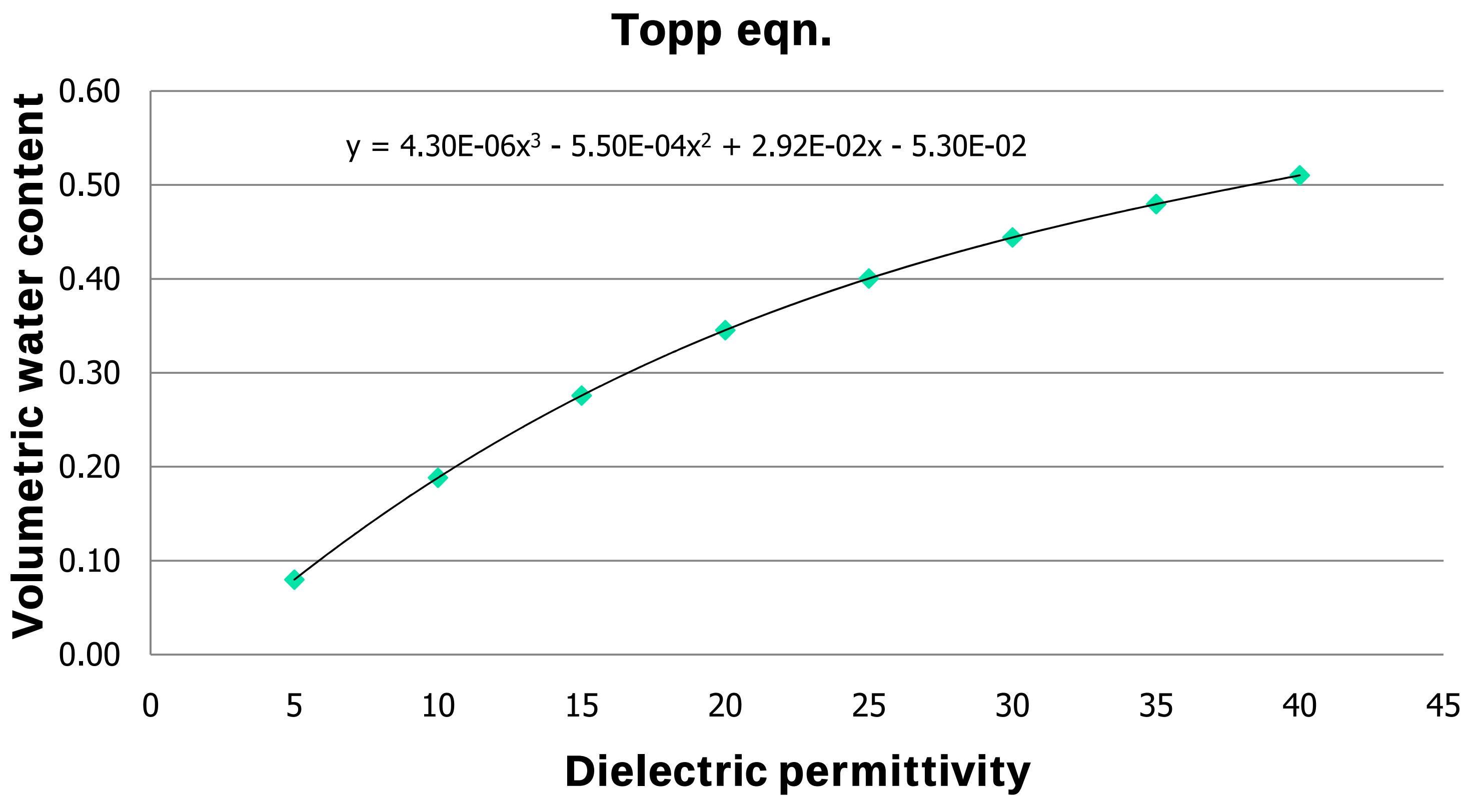
$$\theta = \frac{M_{moist} - M_{dry}}{V_{sample}}$$

Dielectric theory: How it works

- In a heterogeneous medium:
  - Volume fraction of any constituent is related to the total 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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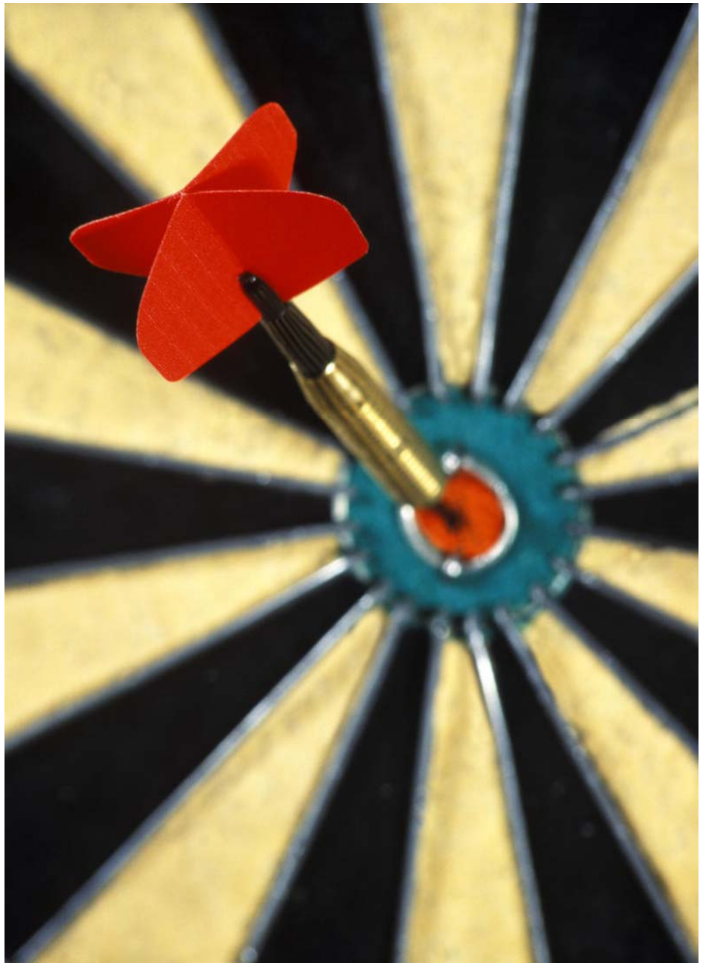
Accuracy

- **Accuracy** - How close the measured value is to the actual (absolute) value.

- **Precision** - The degree of reproducibility of measurement.

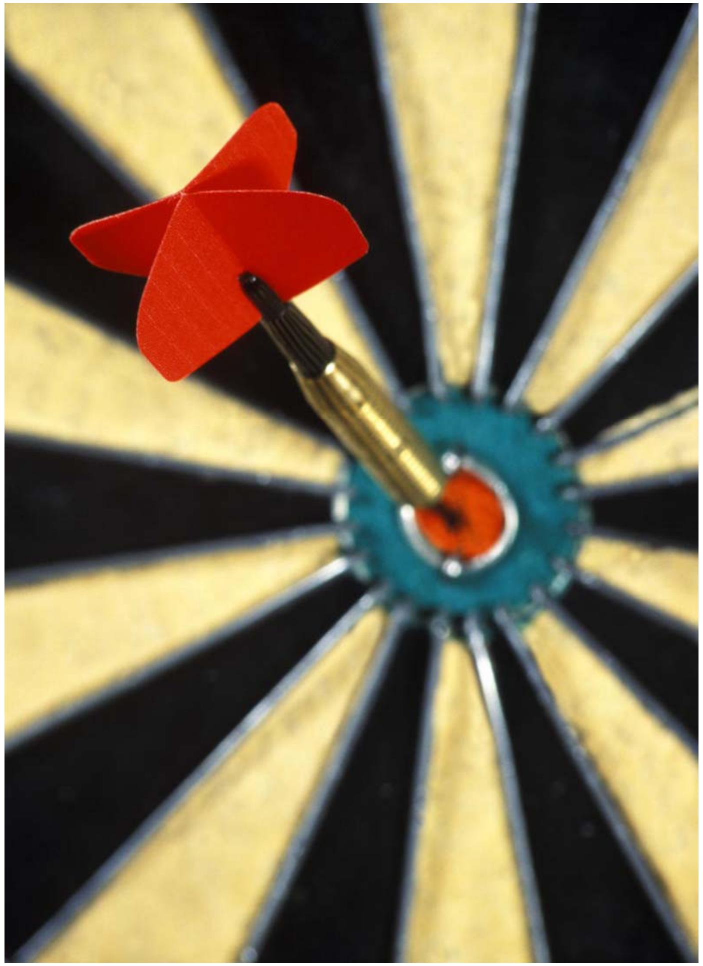
- **Resolution** - The smallest change that can be detected.



Accuracy (of what measurement?)

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

- Can a sensor really have 1% VWC accuracy for all soils?



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

Sensor accuracy

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

Sensor accuracy:
Sensor-sensor repeatability

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

Sensor Accuracy: Temperature effects

- Sensor electronics must have negligible inherent temperature sensitivity

- Dielectric permittivity of soil water is temperature dependent
  - Weak negative correlation

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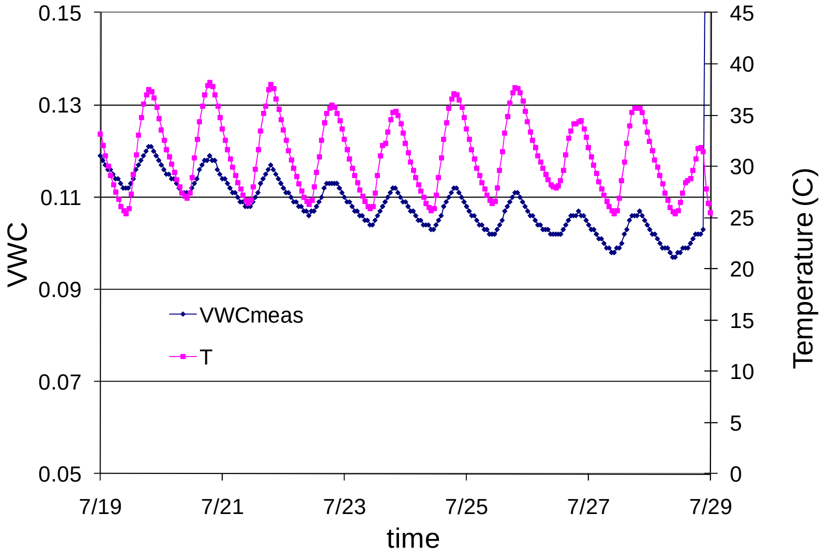
Sensor Accuracy: Temperature effects from EC sensitivity

- Electrical conductivity of soil solution is **highly** temperature dependent
  - Strong positive correlation
  - Often causes diurnal temperature sensitivity
  - Impossible to compensate in electronics
  - Must do correction during data analysis



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Converting dielectric permittivity to VWC

- Commonly called a calibration equation
  - Fundamentally different from dielectric calibration
- 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

Accuracy of permittivity/VWC relationship

$$\varepsilon_b^{1/2} = x_a \varepsilon_a^{1/2} + x_m \varepsilon_m^{1/2} + \theta \varepsilon_w^{1/2}$$

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

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Accuracy of permittivity/VWC relationship

By rearranging, we can get an equation relating water content to:

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

$$\theta = \frac{\varepsilon_b^{1/2} - 1 - (\varepsilon_m^{1/2} - 1)\rho_b / \rho_s}{\varepsilon_w^{1/2} - 1}$$

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Accuracy of permittivity/VWC relationship

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 ±2.5% VWC error

- If we consider organic soils or compacted soils, the error can be much larger.

Accuracy of permittivity/VWC relationship

Effect of mineral permittivity

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

- Mineral permittivity not generally a major source of error (but can be in some situations)

Accuracy of permittivity/VWC relationship

Effect of dielectric permittivity of water

- Dielectric Permittivity of free water is around 80 at room temperature.
  - The dielectric decreases with increasing temperature at about 0.5%/ºC .
  - At a VWC of 20%, a ±20 ºC temperature change results is a ±1.2% change in predicted VWC

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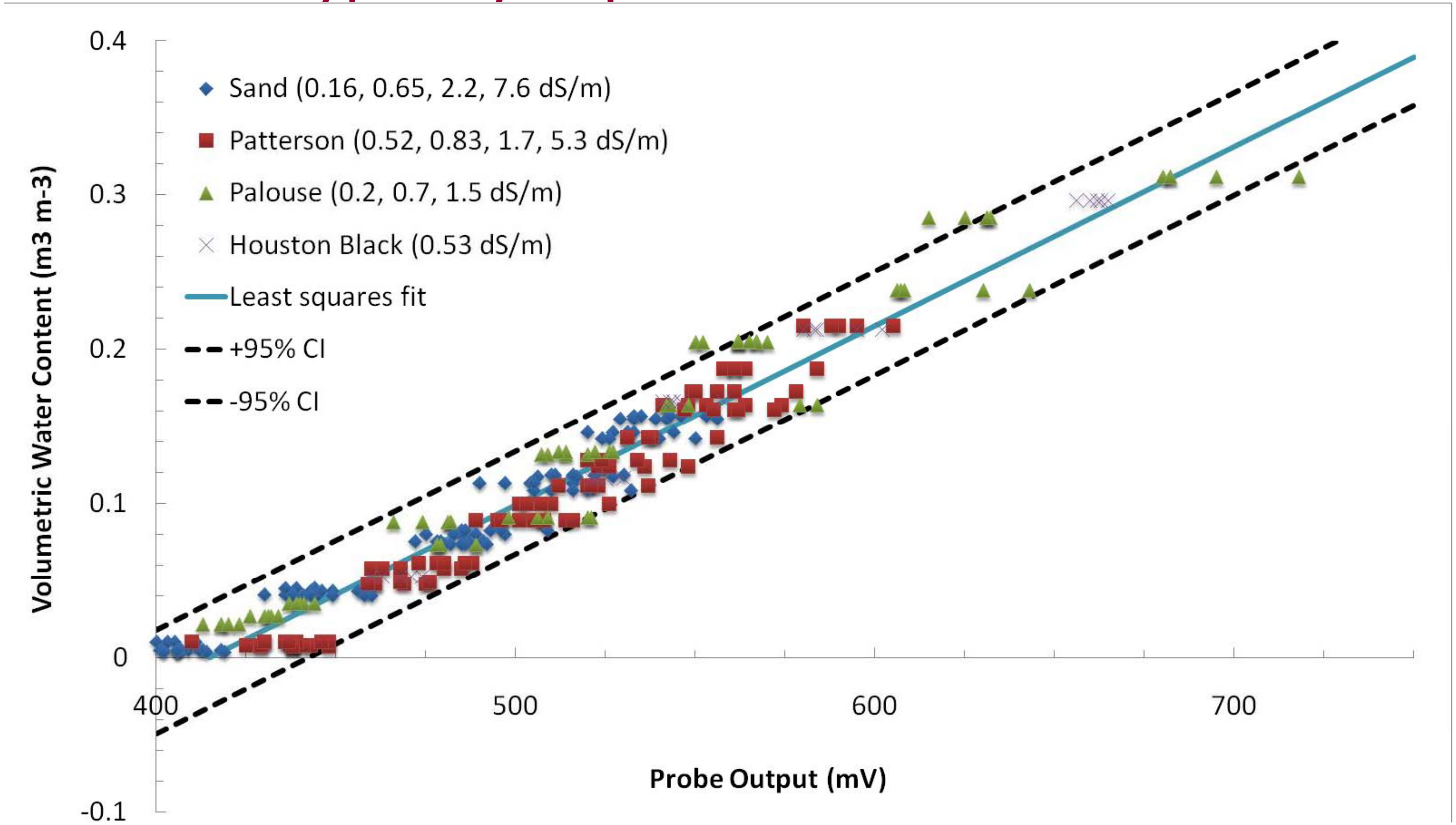
Accuracy of permittivity/VWC relationship

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
- Ice
  - Permittivity = 5 (liquid water = 80)

Generic calibrations

What we typically expect in mineral soil



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Kizito et. al (2008)

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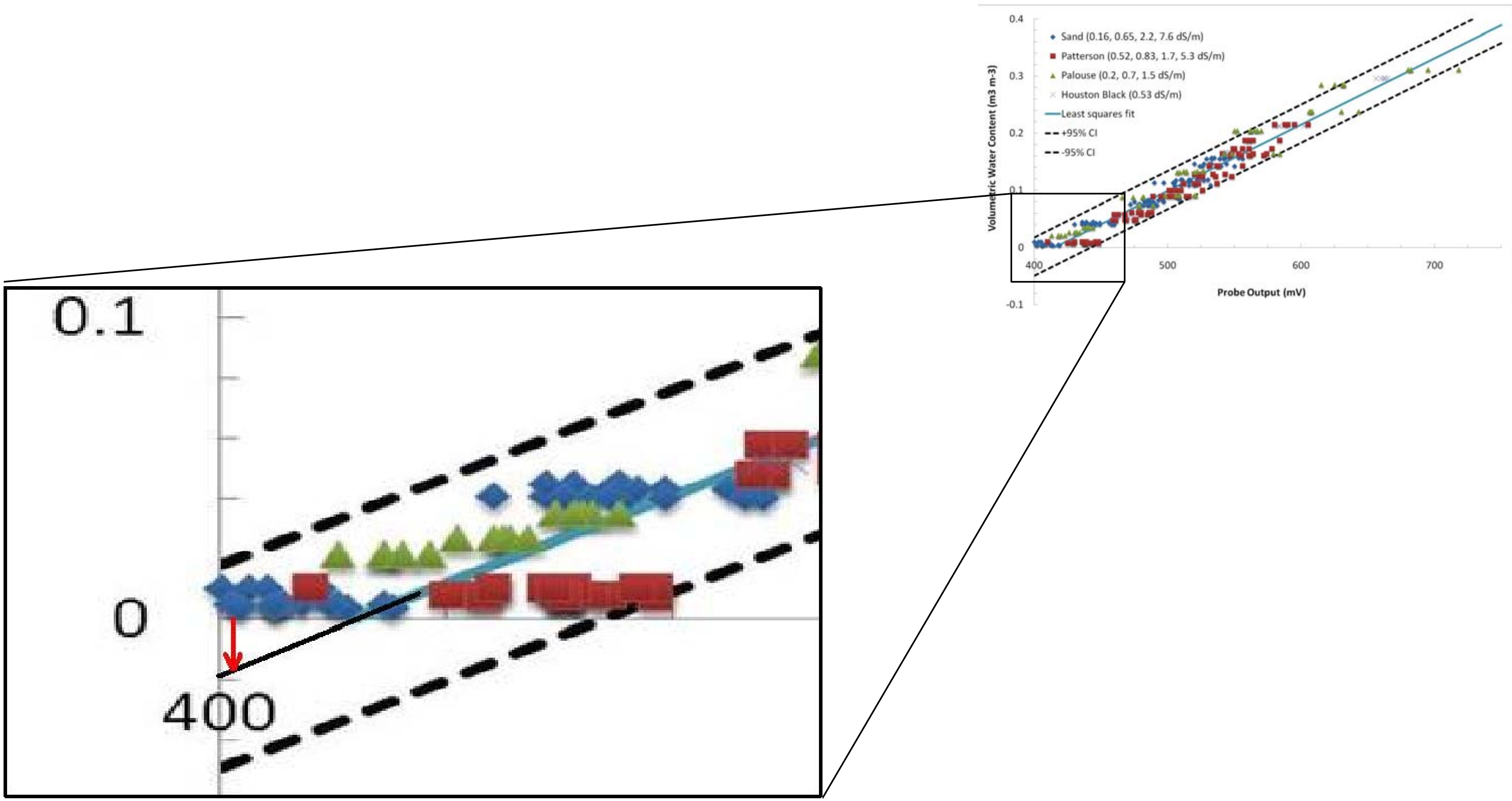
Generic calibrations **fail** when:

- Saturation extract EC is greater than 10 dS/m
- Your soils are not "typical" soils
  - Organic soils
  - Volcanic soils
  - Odd mineralogy (e.g. titanium) soils
  - Non-soil media (potting soil, peat, rockwool, perlite, cocus, etc.)
- Your study requires better than about 3% VWC accuracy

Why do my sensors read negative?

Generic calibration doesn't match your soil



Kizito et. al (2008)

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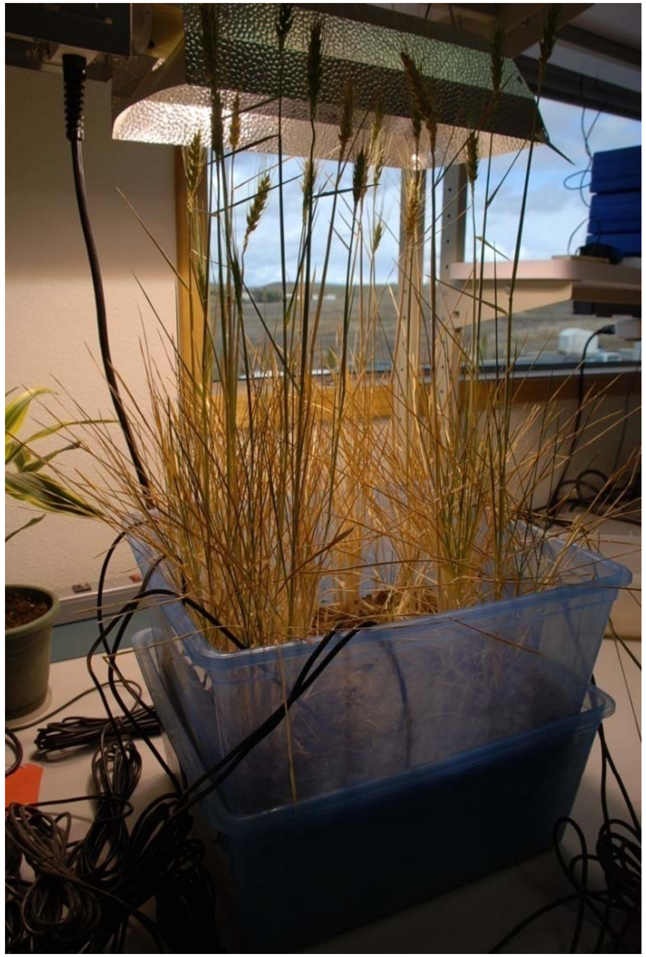
Soil-specific calibrations

- 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 (with or without plants).
- 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

- Heterogeneity in drying pattern
- Results highly dependant upon where the sensor is within the container
- Small amount of work involved, but can take months
- Almost never gives good results

Soil-specific calibrations
Homogenized soil method (recommended)

- Pack dry soil to desired bulk density

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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

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Soil-specific calibrations
Homogenized soil method (recommended)

- Add arbitrary amount of water and mix thoroughly
- Repeat

Soil-specific calibrations
Homogenized soil method

Benefits

- Homogenized soil prevents differences in VWC 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 (dozens of soils/non-soil media calibrated)

- With care, should be able to get VWC accuracy to ±1% VWC

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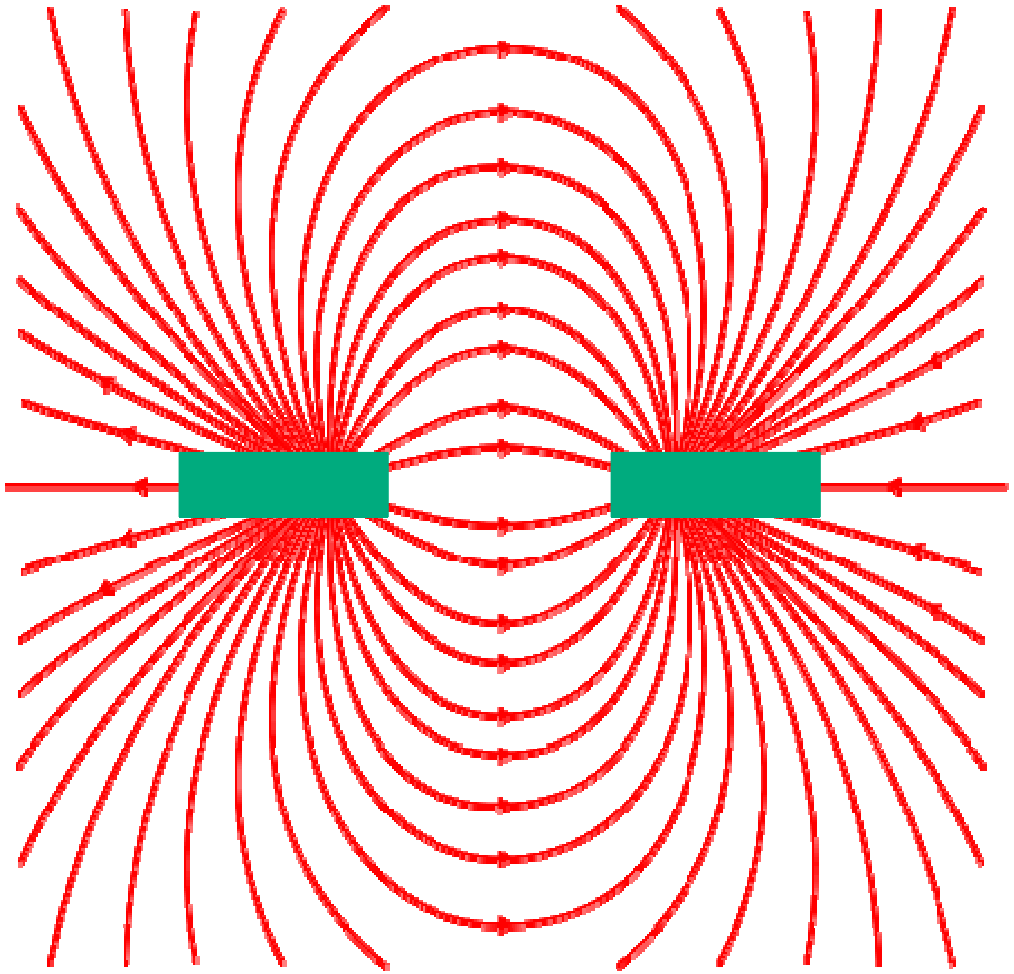
Installation quality

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

Installation – sensitivity of measurement



Installation quality
Voids

- Typically occur near sensor where sensitivity is greatest
- Unsaturated soil
  - Voids drain
  - VWC underestimated
  - ***Often results in negative VWC measurement***

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

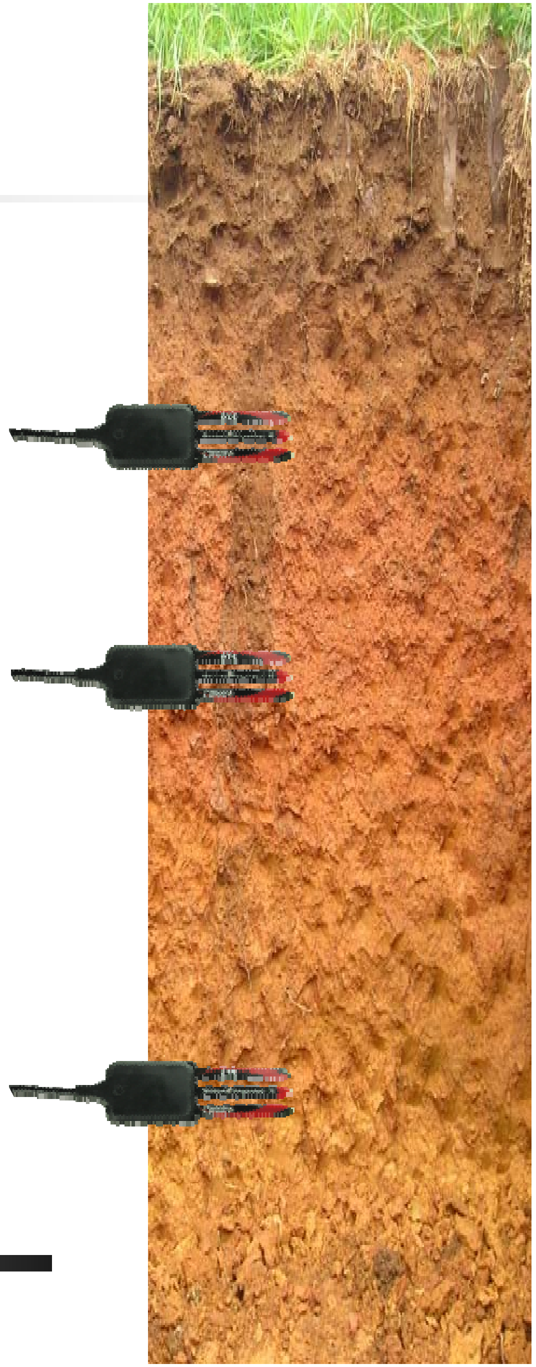
Proper installation
Sidewall

Advantages

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

Disadvantages

- Large excavation (effort)
- Large scale soil disturbance



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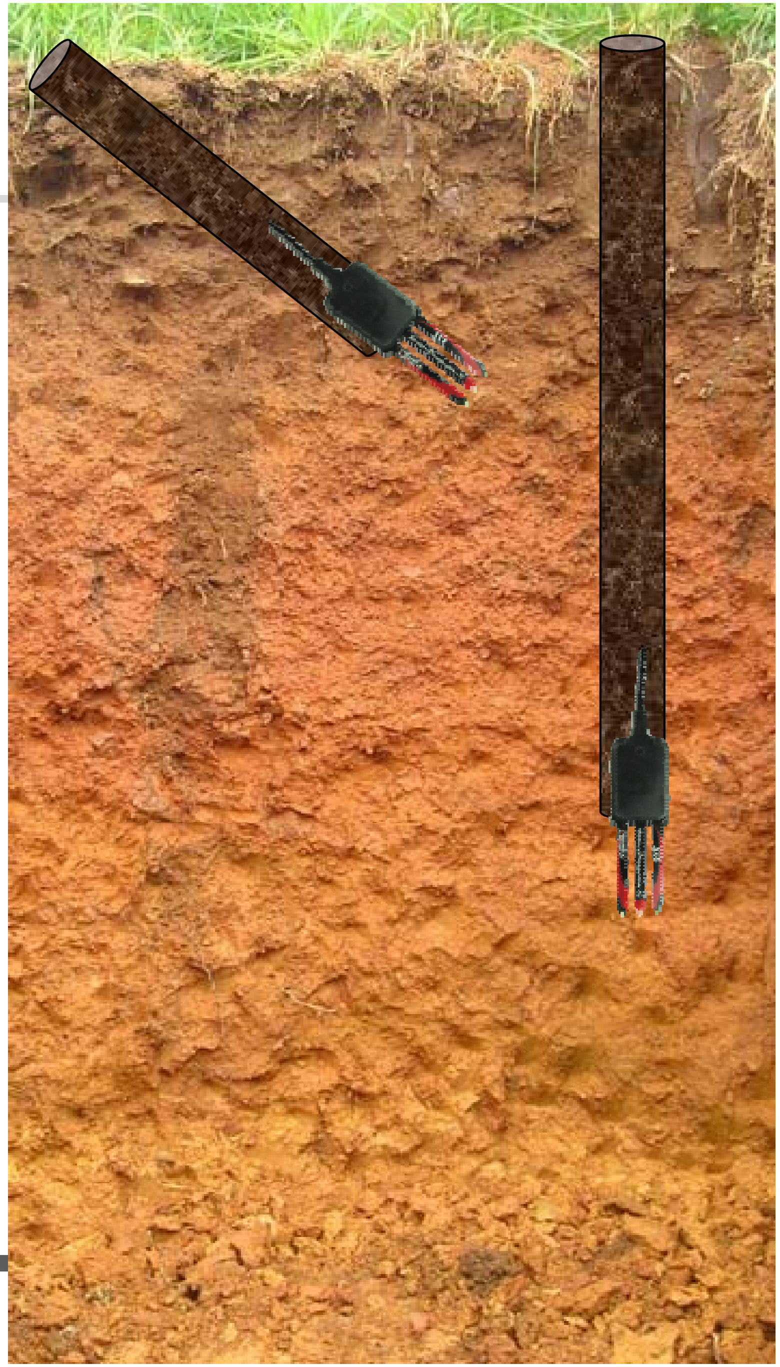
Proper installation
Down hole

- 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

4^{th} 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

- Installation quality
  - Single most important factor for accurate measurements
  - Good sensor contact with soil is critical