Water Content Measurement Methods and Field Applications

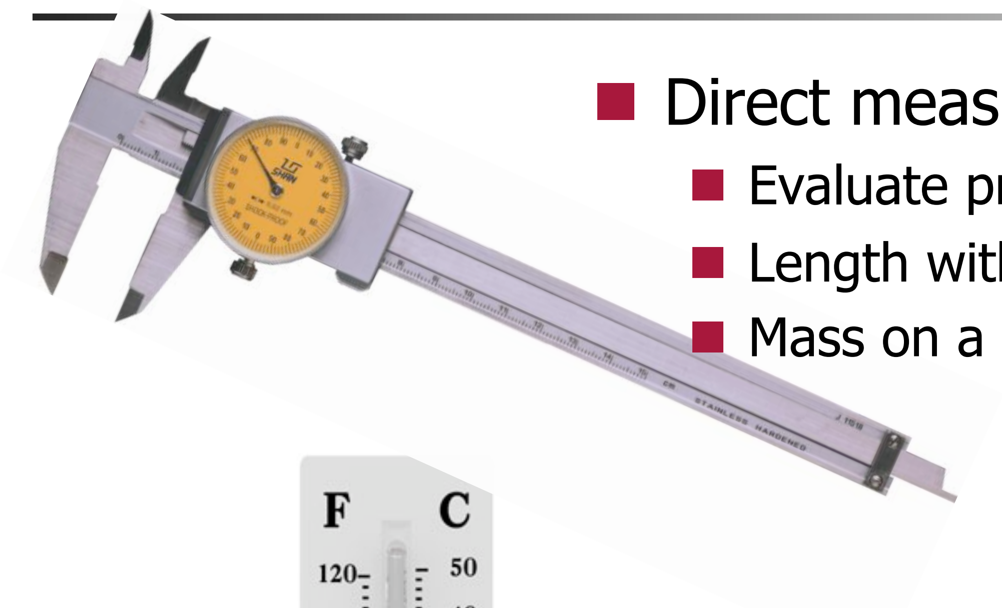
Colin S. Campbell Ph.D.
Research Scientist
Decagon Devices, Inc.

Outline

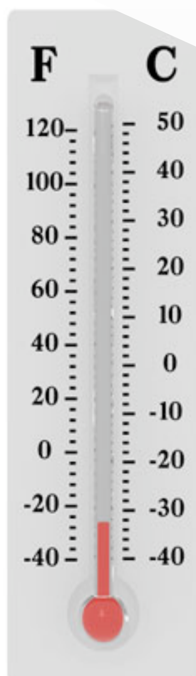
- Direct vs. Indirect measurements
- Water content: Gravimetric vs. Volumetric
- Water content measurement techniques
  - Neutron probe
  - Dual-needle heat pulse
  - Gravimetric sampling
  - Dielectric sensors
    - Time Domain
    - Frequency Domain
- Sensor installation methods
- Field applications/examples

DECAGON DEVICES

Measurement Techniques



- Direct measurements
  - Evaluate property directly
  - Length with calipers
  - Mass on a balance



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

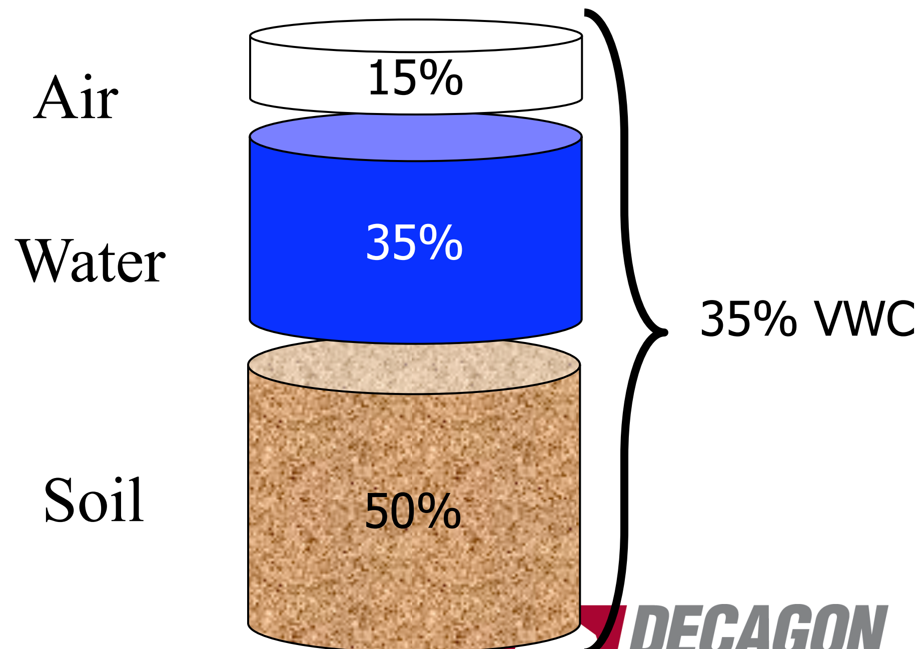
DECAGON DEVICES

Definition: Volumetric Water Content

$$\theta = \frac{V_w}{V_T}$$

- θ is volumetric water content (VWC),
- V_w is the volume of water
- V_T is total sample volume

Separate into constituent parts

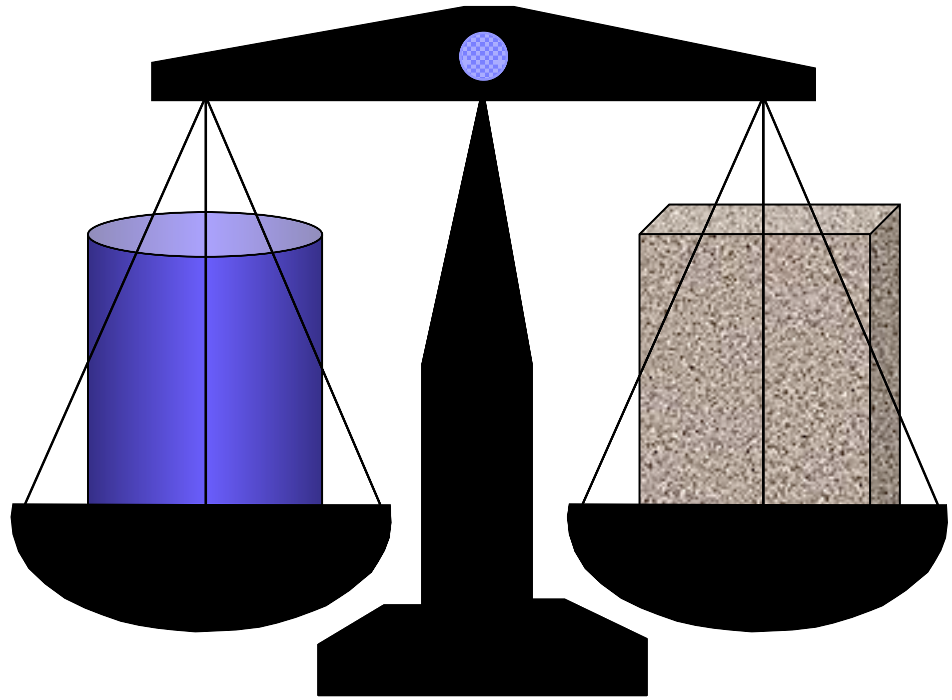


Definition: Gravimetric water content

- Gravimetric water content (w)

$$w = \frac{m_w}{m_d}$$

  - m – mass
  - w – water
  - d – dry solids



Volumetric vs. Gravimetric Water Content

- Volumetric Water Content (VWC)
  - Water volume per unit total volum*e*

Soil bulk Density, ρ_b

- Gravimetric Water Content (GWC)
  - Water weight per unit dry soil weight

$$\rho_b = \frac{m_d}{V_T}$$

- *Two important notes:*
  1. *In situ* field measurement methods can only measure volumetric water content
  2. You must take soil cores of known volume in the field to measure VWC from gravimetric method

DECAGON DEVICES

Direct Water Content: Gravimetric (*w*) Technique

Sample soil (seal in bag) → Weigh on precision balance (wet weight) → Dry @ 105° C for 24 h → Weigh on precision balance (Dry wt)

- Generate volumetric water content
  - Same as gravimetric except soil is sampled with known volume
  - Calibration instructions:
    - www.decagon.com/appnotes/CalibratingECH2OSoilMoistureProbes.pdf

Direct Water Content Measurements

- Advantages
  - Simple
  - Direct measurement
  - Can be inexpensive

- Disadvantages
  - Destructive
    - does not account for temporal variability
  - Time consuming
  - Requires precision balance & oven

Instruments for Measuring *in situ* Water Content (indirect)

- Neutron thermalization
  - Neutron probes
- Dual needle heat pulse probe
- Dielectric measurement
  - Capacitance/Frequency Domain Reflectometery (FDR)
  - Time Domain Reflectometry (TDR)

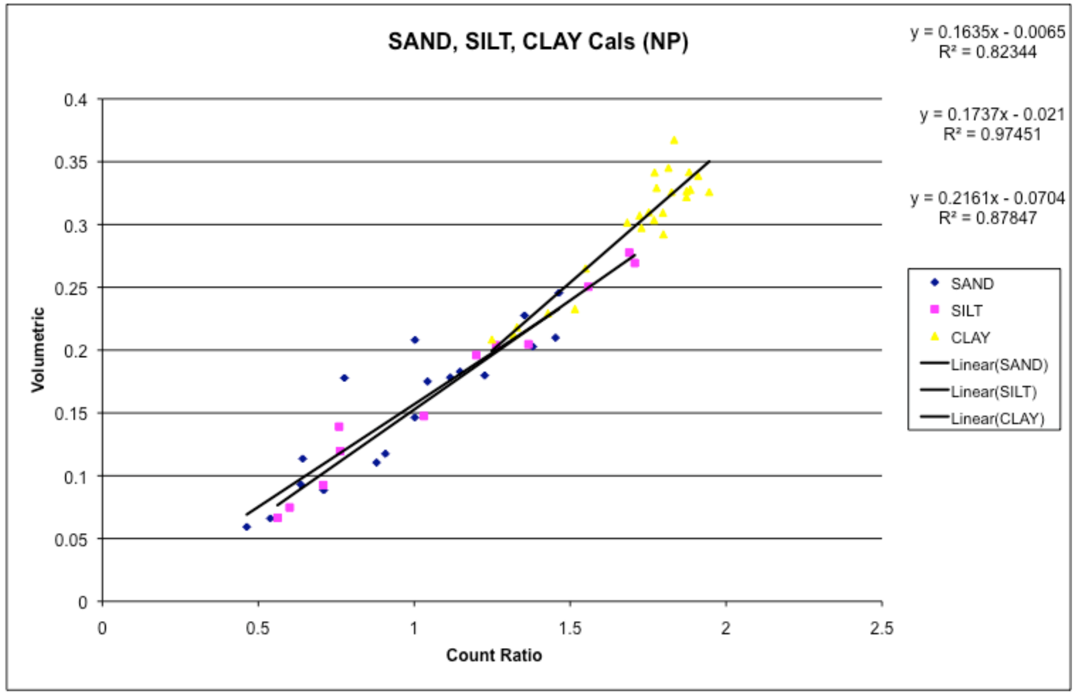
Neutron Thermalization Probe: How They Work

- Radioactive source
  - High-energy epithermal neutrons
- Releases neutrons into soil
  - Interact with H atoms in the soil
    - slowing them down
  - Other common atoms
    - Absorb little energy from neutrons
- Low-energy detector
  - Slowed neutrons collected
    - "thermal neutrons"
  - Thermal neutrons directly related to H atoms, water content

DECAGON DEVICES

Neutron Thermalization Probe: Installation and Calibration

- Installation
  - Auger installation hole
    - Manual auger or Giddings probe
  - Install access tube
- Calibrate sensor
  - Gravimetric method with cores of known volume
  - Single representative site



Data courtesy of Scott Stanislav, Leo Rivera and Cristine Morgan, Texas A&M University

Neutron Probe Measurements

- Measurements
  - Uncap hole
  - Lower probe to specific depth
  - Take reading at each depth
    - 14 s to 2 min per reading
    - Longer read times give better accuracy

Neutron Thermalization Probe

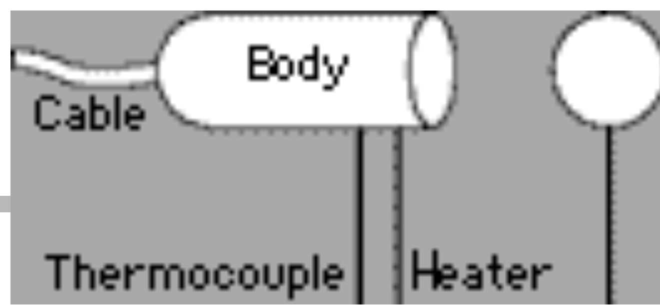
- Advantages
  - Large measurement volume
    - 10 to 20 cm radius, depending on water content
    - Gets away from issues with spatial variability
  - Single instrument can measure multiple sites
  - Insensitive to salinity, temperature

- Disadvantages
  - No continuous record
  - Requires radiation certification to use
  - Expensive
  - Heavy

DECAGON DEVICES

Dual Needle Heat Pulse (DNHP) Technique

- Theory
  - Changes in heat capacity of soil is strongly dependent on water content
  - Create calibration that relates VWC to heat capacity
- Measurement
  - Use dual needle probe
    - One needle contains a heater, the other a temperature measuring device
  - Heat one needle and record temperature over time on the other
  - Use maximum temperature rise (delta T) to calculate heat capacity and convert to VWC



DECAGON DEVICES

Dual Needle Heat Pulse Technique

- Installation
  - Push sensor into soil
    - **Make sure needs do not bend during insertion**
  - Connect to datalogger with precision temperature and data analysis/manipulation capabilities

Dual Needle Heat Pulse Technique

- Advantages
  - Small measurement volume
    - Most location-specific method available
    - Can measure water content around growing seed
- Disadvantages
  - Requires datalogger with precise temperature measurement and analysis
  - Can be susceptible to temperature gradients in soil
    - time
    - depth
  - Integrates small soil volume
  - Fragile

Young et at. (2008) Correcting Dual-Probe Heat-Pulse Readings for Changes in Ambient Temperature, Vadose Zone Journal 7:22-30

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
  - Because of its high dielectric permittivity, changes in water volume have the most significant effect on the total dielectric

Material	Dielectric Permittivity
Air	1
Soil Minerals	3 - 7
Organic Matter	2 - 5
Ice	5
Water	80

Dielectric Mixing Model: FYI

- The total dielectric of soil is made up of the dielectric of each individual constituent
  - The volume fractions, V_x, are weighting factors that add to unity

$$\varepsilon_t^b = \varepsilon_m^b V_m + \varepsilon_a^b V_a + \varepsilon_w^b \theta + \varepsilon_{om}^b V_{om} + \varepsilon_i^b V_i$$

  - Where ε is dielectric permittivity, *b* is a constant around 0.5, and subscripts *t, m, a, om, i,* and *w* represent total, mineral soil, air, organic matter, ice, and water.

Volumetric Water Content and Dielectric Permittivity

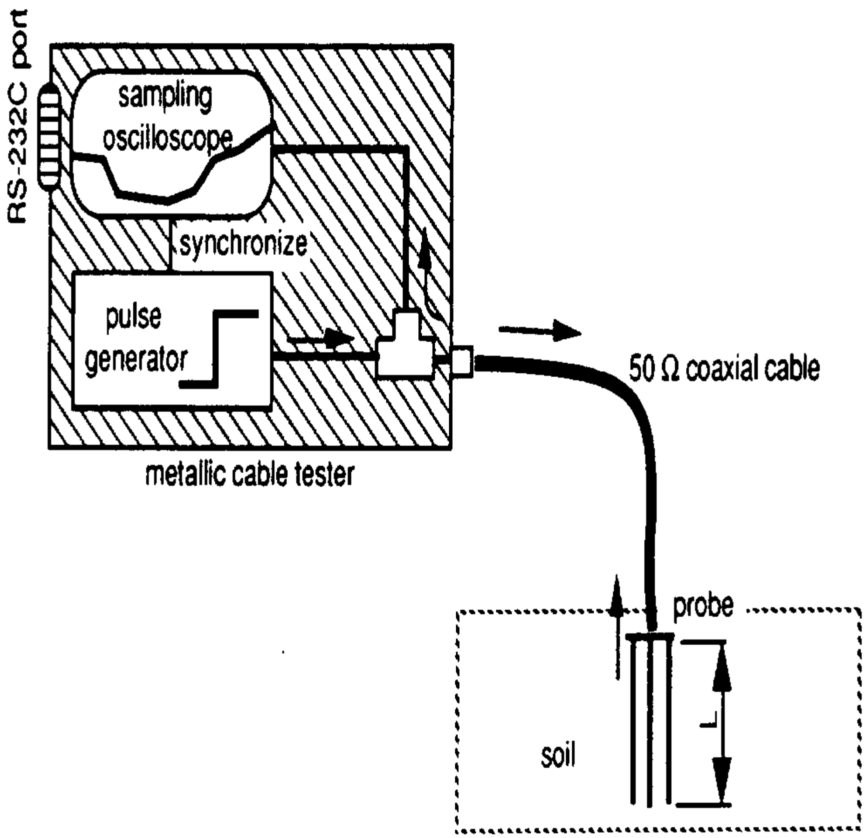
- Rearranging the equation shows water content, θ, is directly related to the total dielectric by

$$\theta = \frac{1}{\varepsilon_w^{0.5}}\varepsilon_t^{0.5} - \frac{(\varepsilon_m^{0.5}V_m + \varepsilon_a^{0.5}V_a + \varepsilon_{om}^{0.5}V_{om} + \varepsilon_i^{0.5}V_i)}{\varepsilon_w^{0.5}}$$

- Take home points
  - Ideally, water content is a simple first-order function of dielectric permittivity
    - Generally, relationship is second-order in the real world
  - Therefore, instruments that measure dielectric permittivity of media can be calibrated to read water content

DECAGON DEVICES

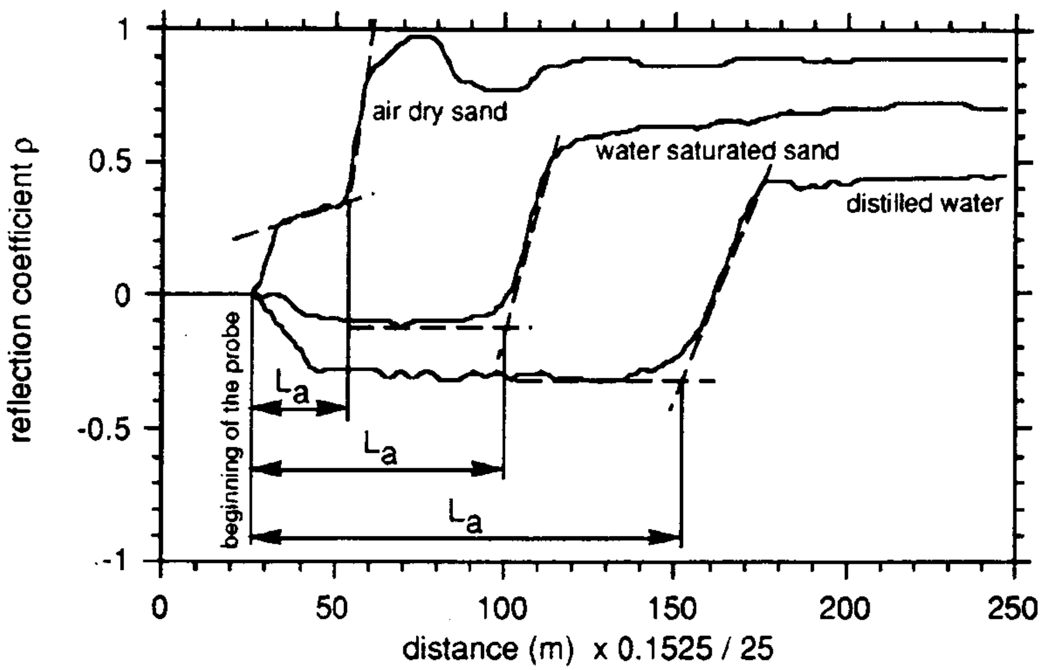
Dielectric Instruments: Time Domain Reflectometry



DECAGON DEVICES

Dielectric Instruments: Time Domain Reflectometry

- Measures apparent length (L_a) of probe from an EM wave propagated along metallic rods
- L_a is related to ε and therefore θ



Time Domain Reflectometery

- Advantages
  - Calibration is relatively insensitive to textural difference
  - Output wave provides electrical conductivity information
  - Good accuracy
  - Insensitive to salinity changes when EC is low to moderate.
- Disadvantages
  - Expensive
  - Does not work at high EC (trace will flatten)
  - Requires waveform analysis (comes with most packages)
  - Sensitive to gaps in soil contact

Time Domain Transmission Sensors

- Variation of time domain reflectometry
  - Look at transmission of wave around loop instead of reflection
- Utilize fast response circuitry to digitize waveform using onboard sensor
- Output dielectric permittivity

DECAGON DEVICES

Time Domain Transmission

Advantages

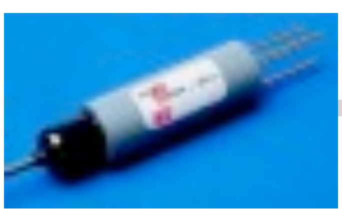
- Lower sensitivity to temperature variation
- Little salinity affect at low to medium electrical conductivity (EC) levels
- Lower cost

Disadvantages

- Small volume of influence
  - Limited field in the soil
- Cannot be installed into undisturbed soil
- Lose signal at high soil ECs

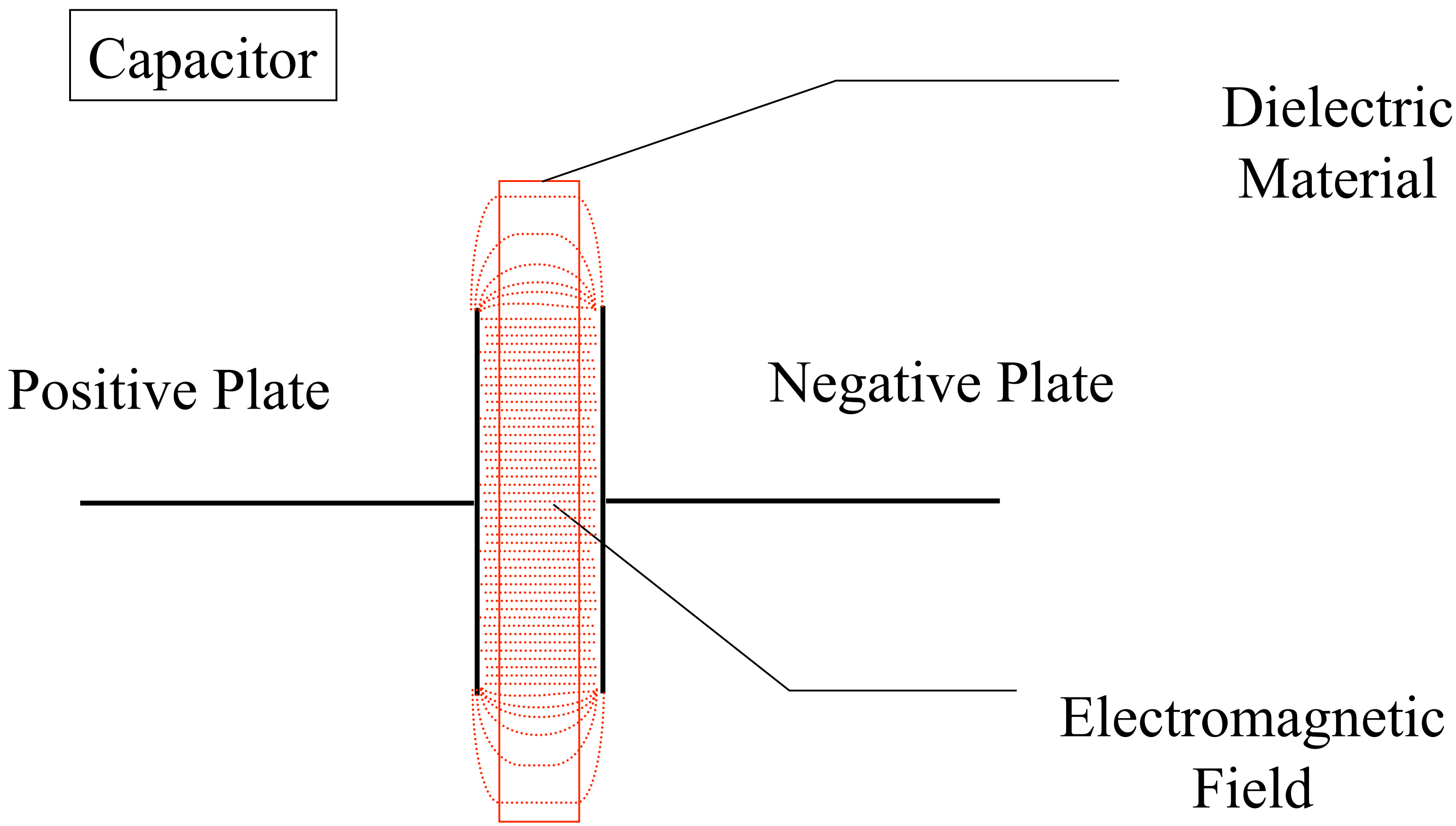
Dielectric Instruments: Capacitor/FDR Sensor Basics

- Sensor probes form a large capacitor
  - Steel needles or copper traces in circuit board are capacitor plates
  - Surrounding medium is dielectric material
  - Electromagnetic (EM) field is produced between the positive and negative plates

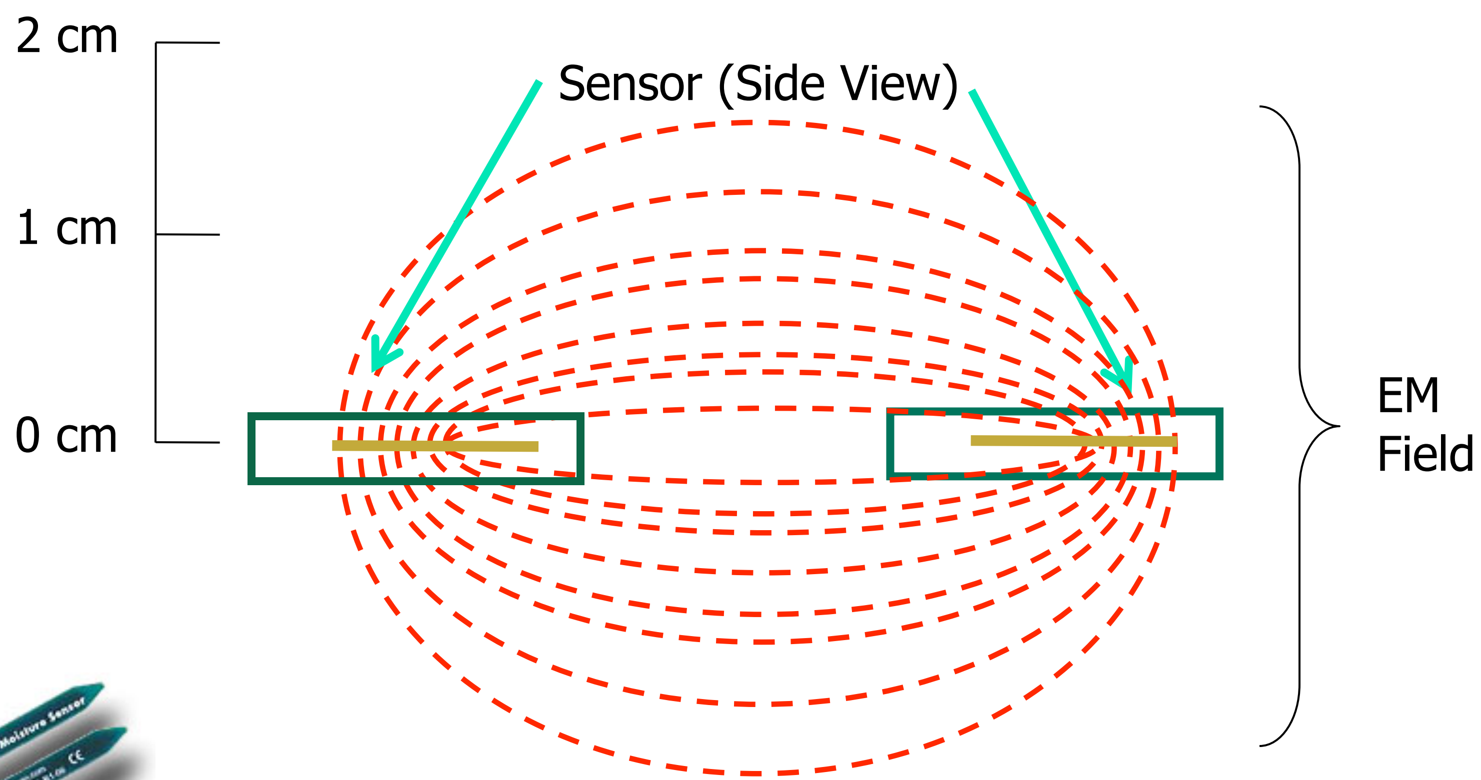


DECAGON DEVICES

Typical Capacitor

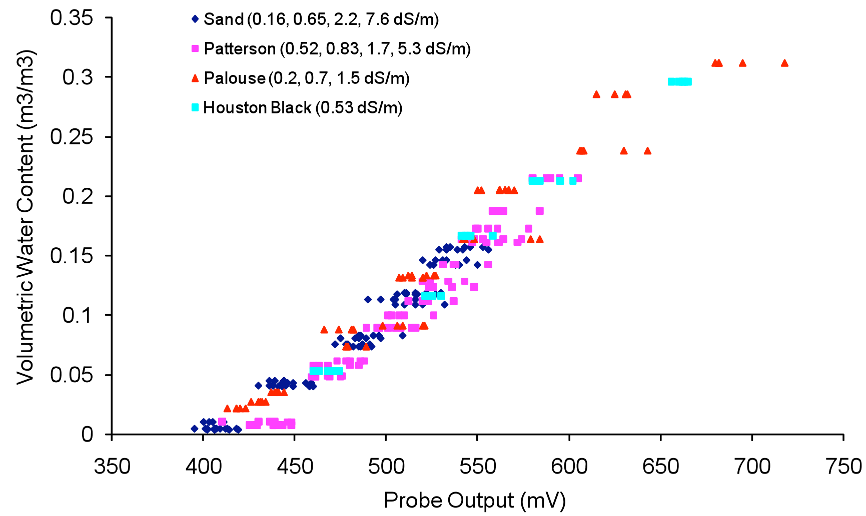


Example: How Capacitance Sensors Function



Getting to Water Content

- Charging of capacitor directly related to dielectric
- Sensor circuitry converts capacitor charge to an output of voltage or current
- Sensor output is calibrated to water content using the **direct** volumetric water content method discussed earlier

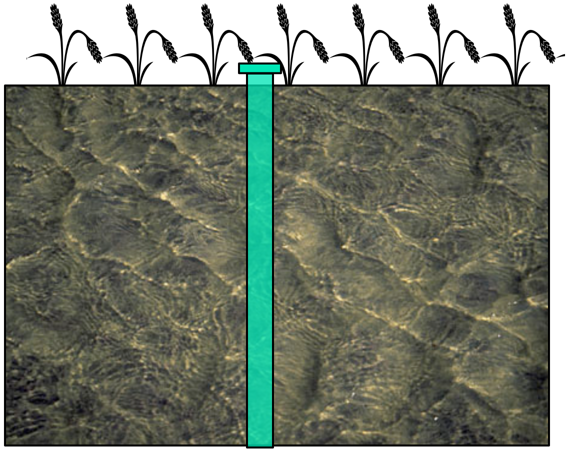


Capacitance/FDR

- Advantages
  - Lower cost
  - Require simple readout device
  - Easy to install/use
  - Best resolution to changes in water content of any method
    - Resolve changes of 0.00001 $m^3\ m^{-3}$
  - Low Power
- Disadvantages
  - Some probes are sensitive to soil texture and temperature fluctuations
    - Depends on probe measurement frequency
  - Some require down-hole installation
  - Sensitive to air gaps in soil contact

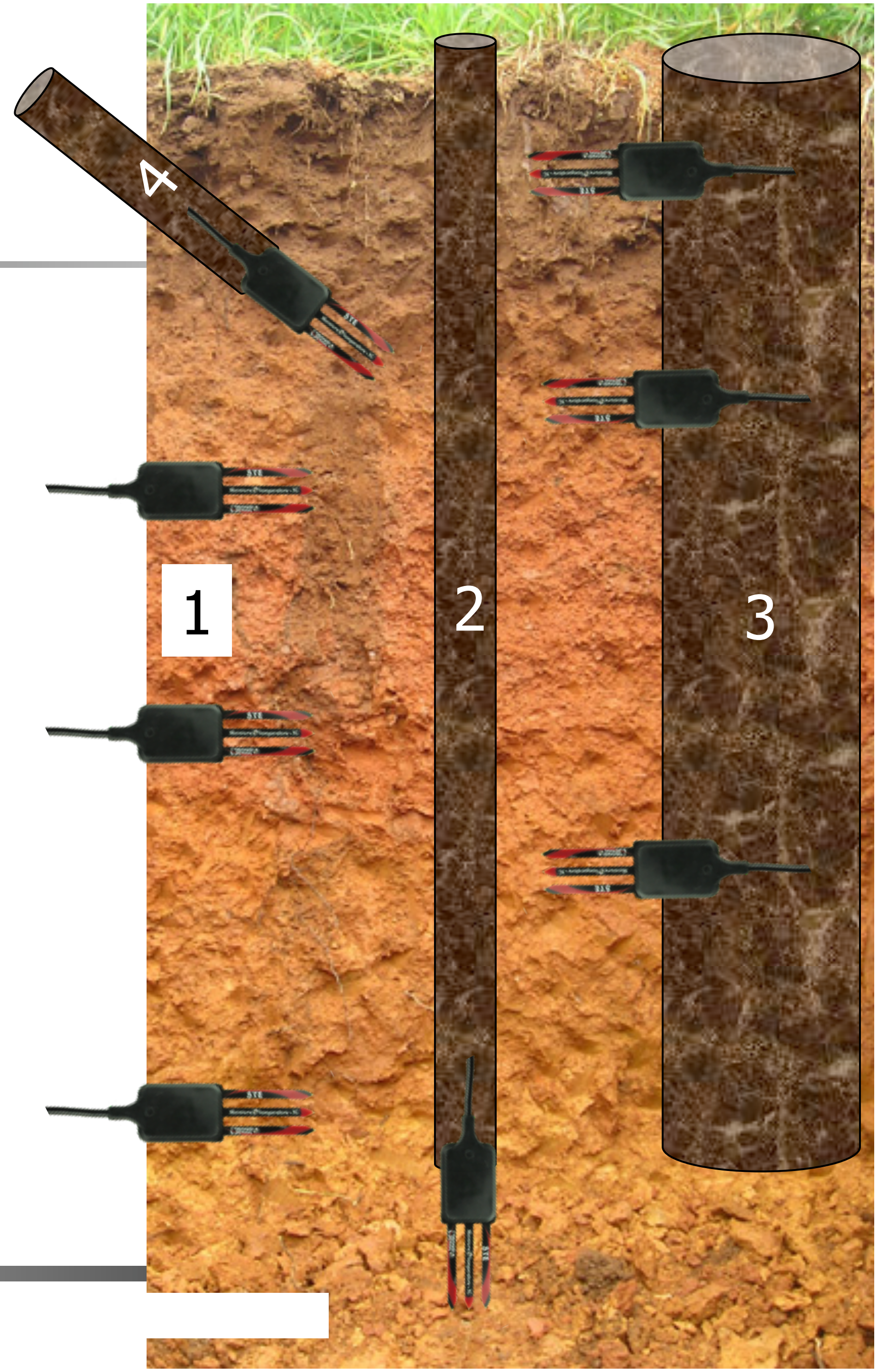
Sensor Installation

- Three types of instruments
  - Access tube
  - Permanent installation
  - "Push-in and Read"
- Access Tube
  - Auger hole to installation depth
  - Insert access tube sleeve into hole
    - Air gaps MUST be minimized during installation of sleeve
  - Install dielectric probe in sleeve and seal OR lower dielectric probe into sleeve at depths of interest



Permanent Installation

- Many techniques for sensors installation
  1. Trench wall
  2. 5 cm diameter auger hole: bottom
  3. 10 cm diameter auger hole: side wall
  4. 45º angled 5 cm auger hole: bottom
- Sensor insertion
  - Sensor width must be vertical not horizontal



Install video: www.decagon.com/videos

Sensor Installation

- "Push-in and Read" Sensors
  - Purpose
    - Spot measurements of VWC
    - Many measurements over large area
    - No need for data on changes in VWC over time
  - Technique
    - Push probe into soil
      - Ensure adequate soil to probe contact
    - Take reading from on-board display

DECAGON DEVICES

Question: What Technique is Best for My Research?

- Answer: It depends on what you want.
  - Every technique has advantages and disadvantages
  - All techniques will give you some information about water content
- So what are the important considerations?
  - Experimental needs
    - How many sites? How many probes at each site?
  - Current inventory of equipment
    - What instruments are available or can by borrowed
  - Budget
    - How much money can be spent to get the data?
  - Required accuracy/precision
  - Manpower available to work
  - Certification
    - People available certified to work with radioactive equipment

Examples: Applying Techniques to Field Measurement

- Case 1: Irrigation scheduling/monitoring
  - Details
    - 20+ sites, measurements from .25 m to 2 m
    - Spread over field system
    - Continuous data collection is desirable
    - Money available for instrumentation
    - Eventually moving to controlling irrigation water
  - Choice
    - Capacitance sensors
      - Good accuracy
      - Inexpensive
      - Easy to deploy into undisturbed soil
      - Radio telemetry available to simplify data collection

DECAGON DEVICES

Examples: Applying Techniques to Field Measurement

- Case 2: Plot monitoring
  - Details
    - 20 measurement locations, 4 m spacing
    - VWC measurements at several depths in each location
    - Measurements required at least daily
    - Labor available to collect data
    - Limited budget
  - Decision
    - Neutron probe
      - Accurate
      - Cost is price of instrument
      - Measures at multiple depths in access tube
      - Reliable

DECAGON DEVICES

Examples: Applying Techniques to Field Measurement

- Case 3: Geostatistical survey of catchment water content
  - Details
    - Point measurement of water content at statistically significant intervals across a catchment
    - Low budget
    - Labor available to take measurements
    - Spatial variability key to analysis
  - Decision
    - Single "Push-in and Read" capacitance instrument
      - Low cost, easy to use
      - No installation necessary
      - Standard calibration available

Examples: Applying Techniques to Field Measurement

- Case 4: Ecosystem water balance
  - Details
    - Studying water balance in ecosystem
      - Soil texture changes significantly with depth
      - Need detailed analysis of water moving through single profile
    - Point measurements of water content at several other locations throughout ecosystem
    - Budget available
  - Decision
    - TDR or multifunctional sensor at detailed water content site
      - Calibration relatively insensitive to textural changes
      - Output can be analyzed for salinity changes
    - Capacitance at remote locations
      - Datalogging and sensors much less expensive
      - Improved sensing technology has made some capacitance sensors relatively insensitive to textural changes too.

Conclusion

- Many choices for field water content measurement
- Several things must be considered to get the right system
- Many resources available to make decisions
  - Manufacturer's websites
  - Listservs/Google Group
    - http://www.sowacs.com
    - AgSciences Google Group: send email to agscience@googlegroups.com
  - Application scientists

DECAGON DEVICES

Which Measurement Technique is Best? Comparison Chart

	Neutron Probe	TDR	TDT	Capacitance
Sensor Costs	Readout and Probe: $5000	Reader: $4-8K Probe: $100+	Reader: $600++, Probe: $180 - $1000	Reader: $150++ Probe: $60-$2000
Time to Install	30 min to 1 h per site	15 to 2 h per site	15 to 2 h per site	15 min to 2 h per site
Installation Pitfalls: Air gaps	Minor problem	Major problem	Major problem	Major problem
Sphere of influence: Radius	Dry: 50 cm Wet: 10 cm	0.5 to 2 cm radius	0.5 cm radius	0.5 to 2 cm radius
Install into undisturbed soil?	Yes	Yes	No	Yes

Which Measurement Technique is Best? Comparison Chart

	Neutron Probe	TDR	TDT	Capacitance
Data Logging?	None	Specialized reader	Digital communication	Standard data logger
Calibration	Required for best accuracy	Required for best accuracy	Required for best accuracy	Required for best accuracy
Accuracy	+/- 0.03 m^3 m^{-3} Increases with calib.	+/- 0.03 m^3 m^{-3} Increases with calib.	+/- 0.03 m^3 m^{-3} Increases with calib.	+/- 0.03 m^3 m^{-3} Increases with calib.
Temperature Sensitivity	Insensitive	Soil dependent, can be significant	Soil dependant, can be significant	Soil/sensor dependent, can be significant
Salinity Sensitivity	Insensitive	Low levels: low; High levels: Fails	Low levels: low; High levels: Fails	Low levels: low; High levels: low to high, probe specific

DECAGON DEVICES

Appendix: Real and Imaginary Dielectric

$$\kappa_a = \kappa' + j\left(\kappa'' + \frac{\sigma}{\omega \varepsilon_o}\right)$$

- Where:
  - κ_a is apparent dielectric permittivity
  - κ' and κ'' are the real and imaginary portion of dielectric constant, respectively
  - σ is the ionic conductivity
  - ω is angular frequency and ε_o is permittivity of free space

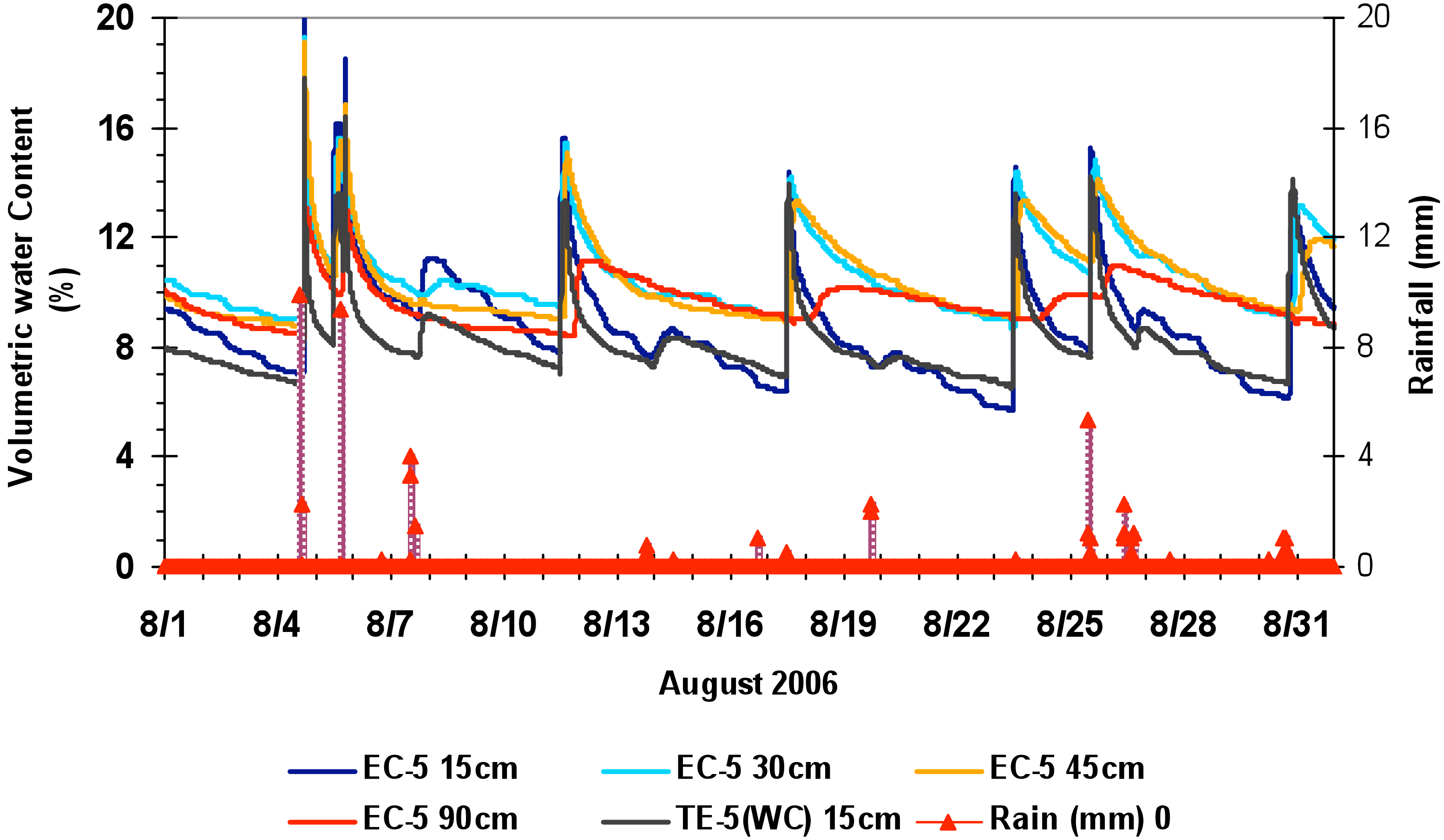
- Apparent permittivity contains a capacitive and conductive component
- Ionic conductivity (σ) is driven by ions in the soil and charged clay surfaces
  - σ is strongly dependent on temperature
  - Ionic affect decreases with measurement frequency

DECAGON DEVICES

Applications

- Irrigation scheduling and control
- Ecosystem/crop water balance
- Water use, efficiency
- Hydrologic monitoring
  - Hydropedology
- Catastrophic event monitoring

What can I expect to see in the field?



Data courtesy of W. Bandaranayake and L. Parsons,
Univ. of Florida Citrus Research and Education Center

DECAGON DEVICES