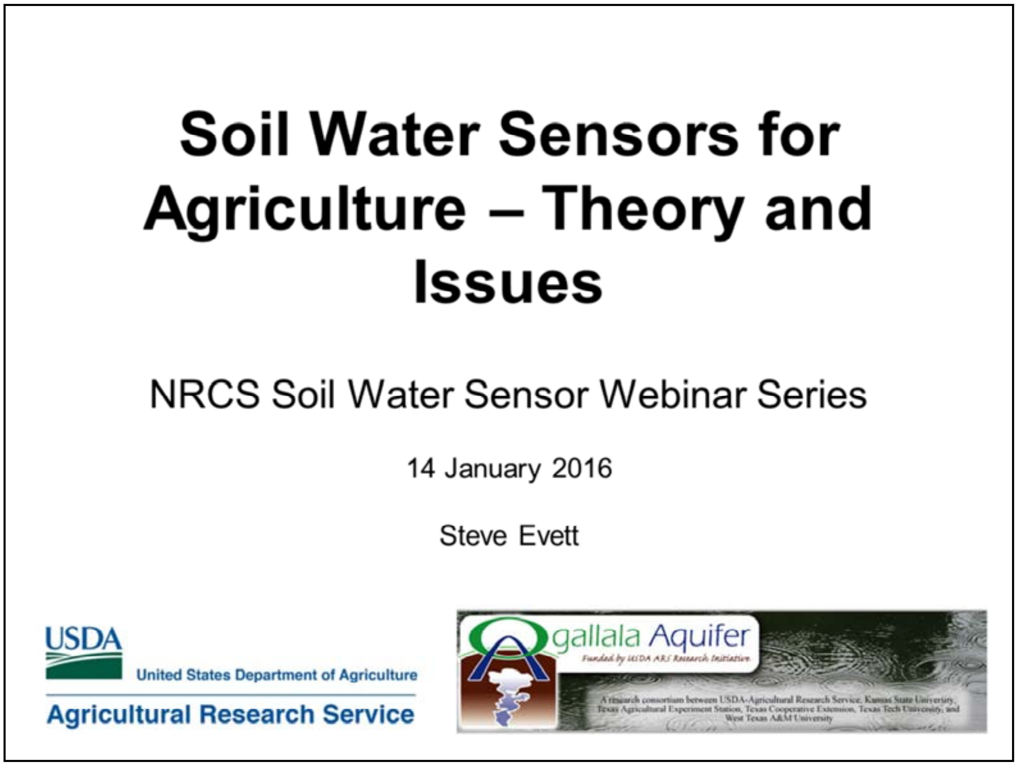


Soil Water Sensors for Agriculture – Theory and Issues

NRCS Soil Water Sensor Webinar Series

14 January 2016

Steve Evett

USDA
United States Department of Agriculture
Agricultural Research Service

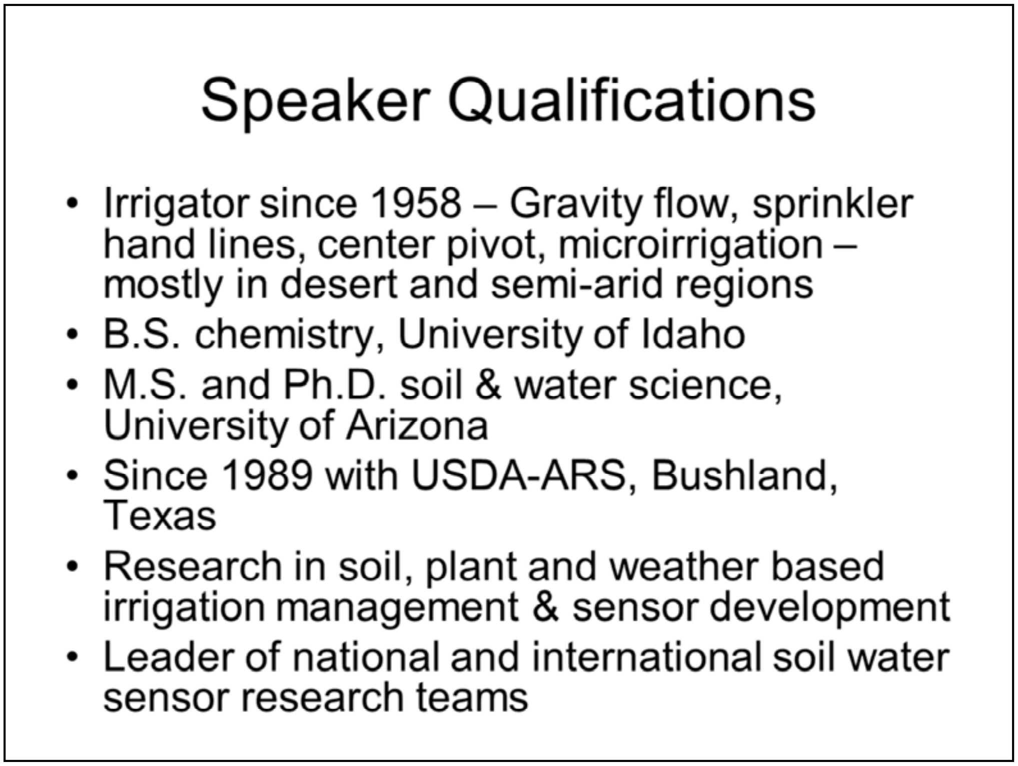
Ogallala Aquifer
Funded by USDA ARS Research Initiative
A research consortium between USDA-Agricultural Research Service, Kansas State University, Texas Agricultural Experiment Station, Texas Cooperative Extension, Texas Tech University; and West Texas A&M University

Soil Water Sensors for Agriculture – Theory and Issues

NRCS Soil Water Sensor Seminar Series, January 14, 2016, 10:30 am

Soil water sensors have been used for irrigation and water management in agriculture for many years, but with limited success in many cases. Nonetheless, the use of soil water sensors in increasing as water scarcity increases and, conversely, problems associated with over irrigation also increase. Common problems with soil water sensing included sensor failure, problems with wiring, lack of or failure of data telemetry, inaccurate data, lack of timely data, too laborious and interference from dynamic soil temperature and bulk electrical conductivity changes. There are many sensors available, but only four main technologies: neutron thermalization, resistance blocks, capacitance sensing (frequency domain sensing), and travel time sensing (time domain reflectometry and time domain transmission modes). Understanding the theory of these offers insight into what a user can expect from each technology in terms of accuracy, stability and representativeness of the readings. The presentation will cover the types of sensors available, the operational theory of each sensor type, and explanations, with examples, of how the physical theory of operation dictates the limits of sensor calibration and performance, and of sensor representativeness in given soils.

This webinar will be followed by another, more focused on applications: “Soil Water Sensors for Agriculture – Applications and Usefulness” on February 11, 2016



Speaker Qualifications

- Irrigator since 1958 – Gravity flow, sprinkler hand lines, center pivot, microirrigation – mostly in desert and semi-arid regions
- B.S. chemistry, University of Idaho
- M.S. and Ph.D. soil & water science, University of Arizona
- Since 1989 with USDA-ARS, Bushland, Texas
- Research in soil, plant and weather based irrigation management & sensor development
- Leader of national and international soil water sensor research teams

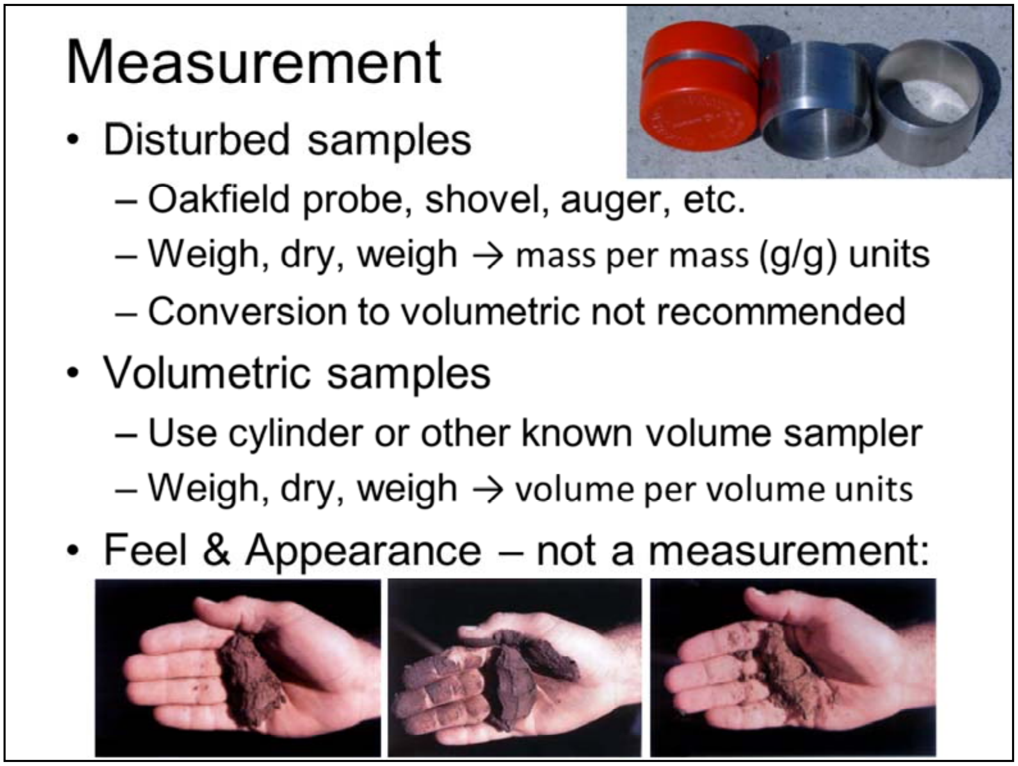
Steven R. Evett is a Senior Research Soil Scientist and Lead Scientist with the USDA Agricultural Research Service, Conservation and Production Research Laboratory, Bushland, Texas. Dr. Evett uses field measurements, electronic sensing and automation systems and energy and water balance models to study irrigated crop water use, irrigation methods and automation as they affect crop water productivity, as well as water content sensing methods used to control irrigation and to quantify crop water use. In addition to research locations in the USA, he has had research projects in Egypt, the Middle East and Uzbekistan on crop water use, irrigation scheduling and soil water measurement; and he has worked in China, Egypt, Jordan and the USA to build and use weighing lysimeters to measure crop water use. Since 2003, Dr. Evett has been the ARS research coordinator for the Middle East Regional Irrigation Management Information Systems (MERIMIS) Project, which has research and extension partners in Israel, Jordan and the Palestinian Authority (http://www.merimis.org/index.html). He is a graduate of the University of Idaho and the University of Arizona, and was raised on an irrigated dairy farm in Southern Idaho. Dr. Evett is a Fellow of the Soil Science Society of America and of the American Society of Agronomy; and he has received the Soil Science Society of America (SSSA) Don and Betty Kirkham Soil Physics Award, the SSSA Applied Soil Science Research Award, the U.S. Dept. of Energy Federal Energy and Water Management Award and the USDA-ARS Technology Transfer Award (twice: 1999 for ET work and 2012 for soil water sensor work). He is a past President of the Texas Council of Chapters of the Soil and Water Conservation Society, and past associate editor of Agronomy Journal and of the Vadose Zone Journal, and he currently is on the Editorial Board of Agricultural Water Management. He is author/coauthor of 277 publications, including 25 book chapters.

Premise

- If we are going to recommend soil water sensors and sensing systems, we should know how they work and where, when and why they may or may not work well

Soil Water Measurement & Sensing

- **Measurement methods involve taking soil samples and measuring the water removed by drying**
  - Samples may have a defined volume or not
  - Most common drying method is an oven
- **Sensing methods involve measuring some response to applied force/radiation**
  - Radiation may be electromagnetic or particle
  - Water content is estimated from the measured response using a calibration



Measurement

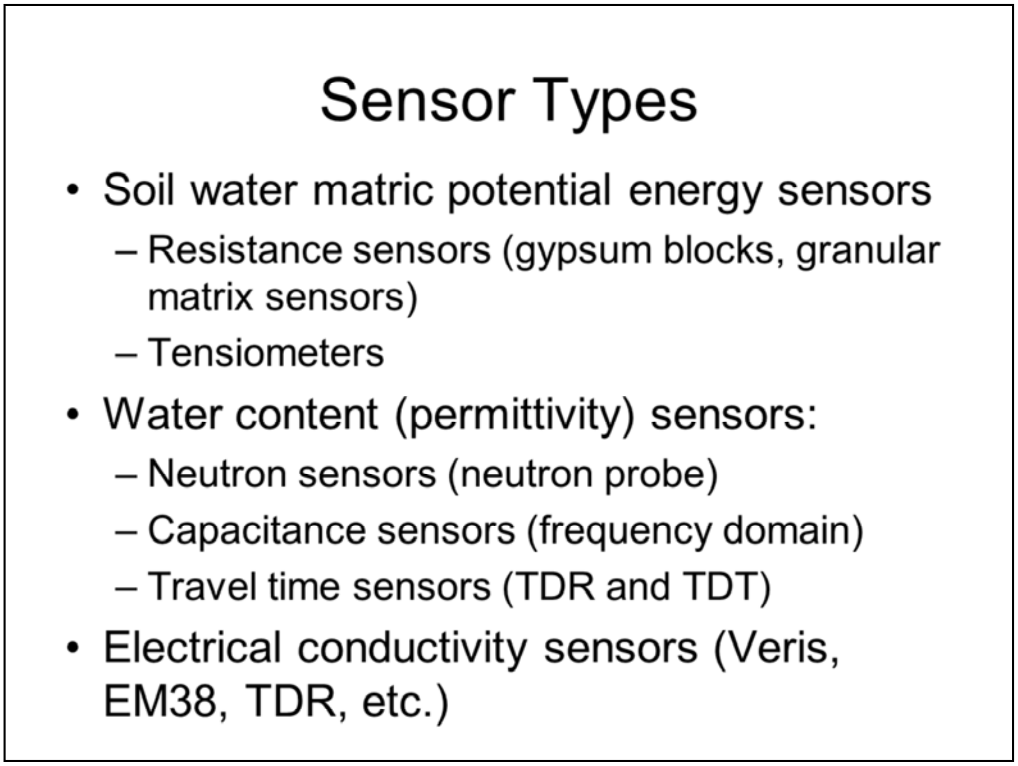
- Disturbed samples
  - – Oakfield probe, shovel, auger, etc.
  - – Weigh, dry, weigh → mass per mass (g/g) units
  - – Conversion to volumetric not recommended
- Volumetric samples
  - – Use cylinder or other known volume sampler
  - – Weigh, dry, weigh → volume per volume units
- Feel & Appearance – not a measurement:

Soil water measurement differs from soil water sensing in that the actual amount of water in the soil is measured using mass balance methods while sensors respond to some surrogate property of soil that is related to its water content. With sensors there may be interferences from soil properties that confuse the response to the surrogate property such that the water content is rendered inaccurate.

For irrigation scheduling, we need volumetric water content values because we need to know how much water to apply to the soil. Measurement methods that give volumetric water contents all involve taking a sample of known volume, usually with a cylindrical ring or probe. Methods that take an unknown volume of soil (shovel, Oakfield probe, auger, etc.) can only give the water content in terms of mass of water per unit mass of soil (gram per gram, oz per oz, etc.). While it is possible to convert the mass basis water content to a volumetric water content using the value of the soil bulk density, this procedure is not recommended because the innate variability of soil bulk density is so large that the volumetric water content values can be quite inaccurate.

The NRCS has publicized the Feel and Appearance method for estimating soil water content. The method relies on a series of charts and photographs showing the feel and appearance of several major soil texture classes at a series of water contents. With sufficient practice, one can learn to estimate water content to within about 0.05 inch/inch (m^3 m^{-3}).

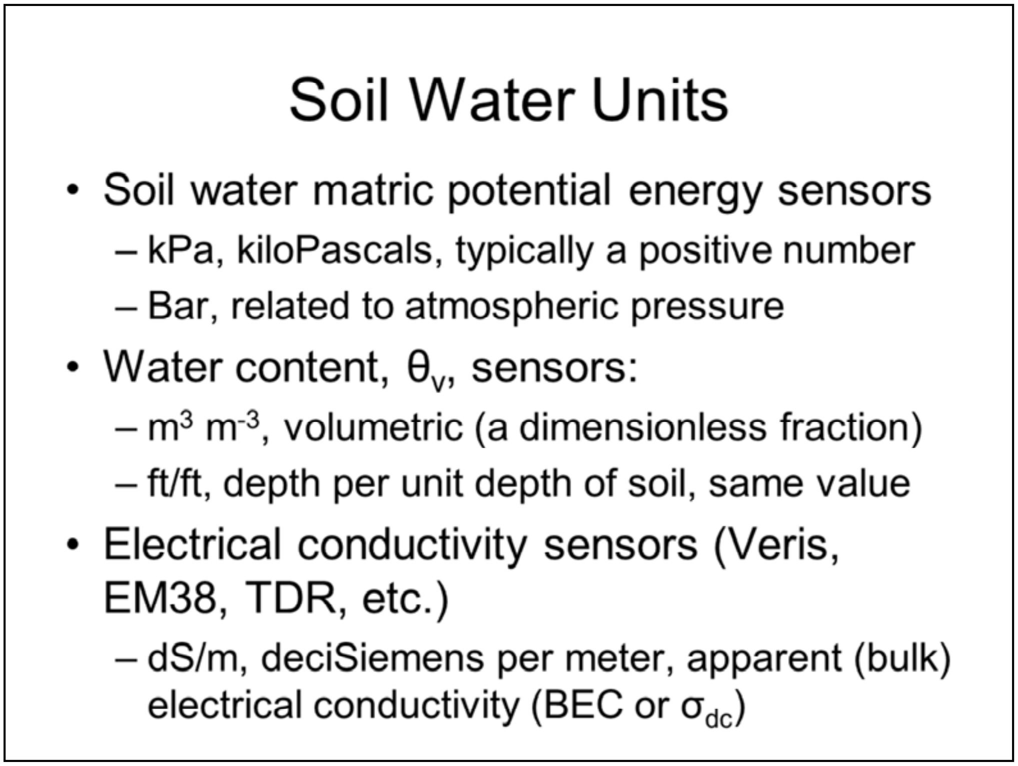
These methods are becoming less used due to the labor requirement since they involve much time in the field to obtain and evaluate samples from the surface and lower in the root zone.



Sensor Types

- Soil water matric potential energy sensors
  - Resistance sensors (gypsum blocks, granular matrix sensors)
  - Tensiometers
- Water content (permittivity) sensors:
  - Neutron sensors (neutron probe)
  - Capacitance sensors (frequency domain)
  - Travel time sensors (TDR and TDT)
- Electrical conductivity sensors (Veris, EM38, TDR, etc.)

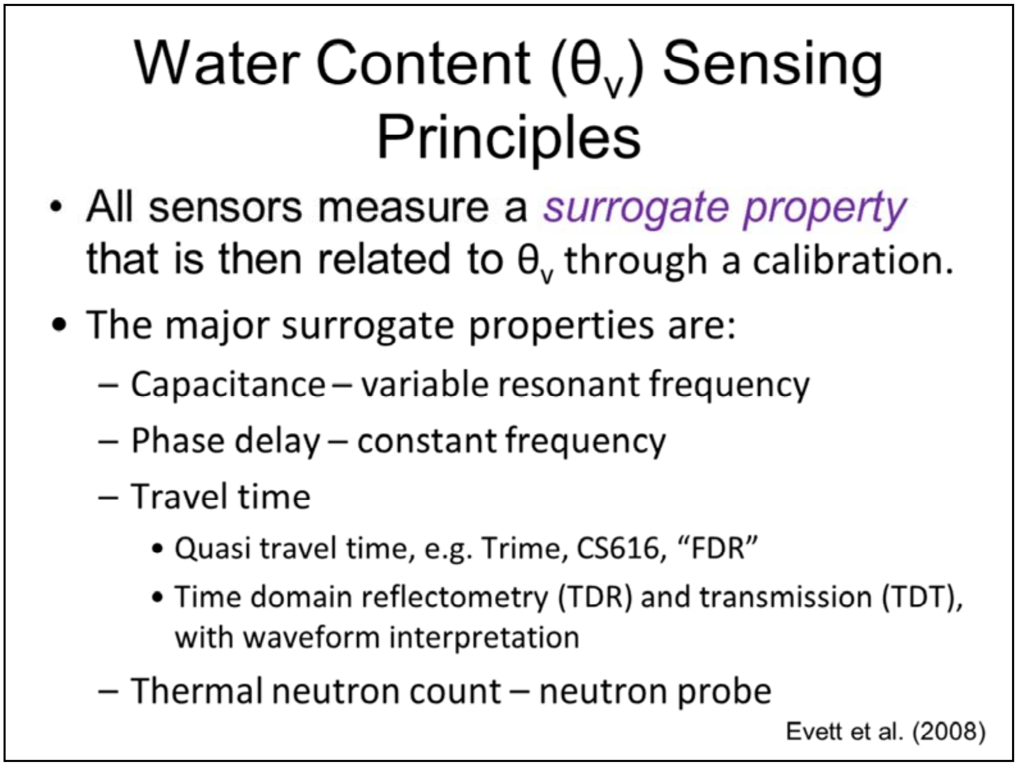
Modern sensors vary widely in their ease of use, cost and data transmission features incorporated or made available by vendors. Sensors may be intended to respond to soil matric potential (the energy with which water is held in the soil and which directly affects the plant water uptake), the soil volumetric water content, the soil bulk electrical conductivity or a combination of these. The matric potential sensors are of two types, the resistance sensors, which measure the electrical resistance within a porous block in contact with the soil, and the tensiometers, which measure directly the soil water potential through a porous cup in contact with the soil, using a pressure sensor or gage. The water content sensors measure either the number of thermal neutrons, which increases with water content, the resonant frequency of an electronic oscillator coupled to a capacitor whose electromagnetic field passes through the soil (frequency domain, FD, sensors), or the travel time of an electric pulse traveling along a waveguide (electrodes) inserted into the soil (time domain sensors). The time domain sensors can operate in either reflection mode (time domain reflectometry, TDR) or transmission mode (time domain transmission, TDT).



Soil Water Units

- Soil water matric potential energy sensors
  - kPa, kiloPascals, typically a positive number
  - Bar, related to atmospheric pressure
- Water content, θ_v, sensors:
  - $m^3\ m^{-3}$, volumetric (a dimensionless fraction)
  - ft/ft, depth per unit depth of soil, same value
- Electrical conductivity sensors (Veris, EM38, TDR, etc.)
  - dS/m, deciSiemens per meter, apparent (bulk) electrical conductivity (BEC or σ_{dc})

It is important to understand the units of values reported by a sensor. Common units reported by matric potential sensors include kiloPascals (kPa) and bars (one bar is one standard atmosphere of pressure, or the pressure at sea level). Values can be either negative (reporting pressure, which is always less than zero or zero if the soil is completely filled with water) or positive (reporting tension or suction). Water content sensors typically report in units of volume of water per volume of soil (volumetric water content, which is dimensionless). But water contents sensors also can report in units of depth per unit depth of soil (e.g., foot per foot, inch per inch, cm per cm, etc.). The values of volume per unit volume and depth per unit depth are the same. Some water content sensors report in units of percentage (%), which is discouraged because it becomes confusing.



Water Content (θ_v) Sensing Principles

- All sensors measure a *surrogate property* that is then related to θ_v through a calibration.
- The major surrogate properties are:
  - – Capacitance – variable resonant frequency
  - – Phase delay – constant frequency
  - – Travel time
    - Quasi travel time, e.g. Trime, CS616, “FDR”
    - Time domain reflectometry (TDR) and transmission (TDT), with waveform interpretation
  - – Thermal neutron count – neutron probe

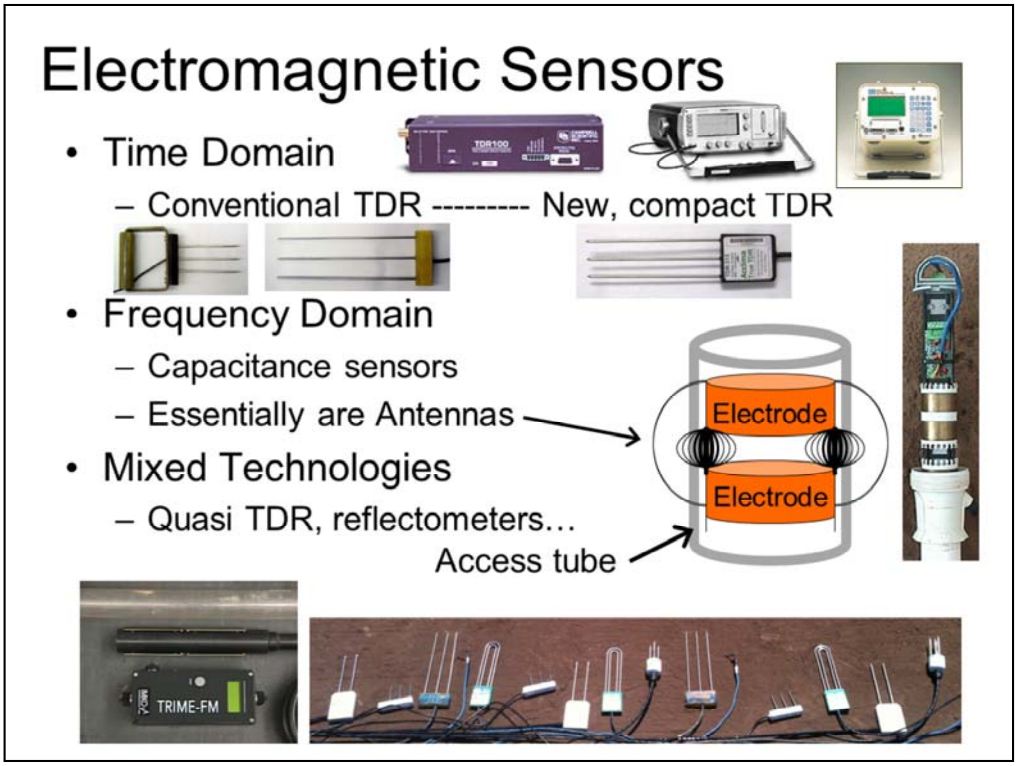
Evett et al. (2008)

Sensors all measured a surrogate property that is related in some water to soil water content or potential. Evett et al. (2008) studied all soil water sensor types and several different sensors within each type in a five-year international study. Their recommendations are reported in a book that is freely available online. The book describes the operating principles of major sensor types and give tips concerning their use in the field. They recommended that capacitance sensors not be relied on for irrigation scheduling due to the inaccuracies discovered. They did recommend the neutron probe and conventional TDR and TDT methods if they use waveform analysis methods to determine travel time.

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen. 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. 131 pp. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

Neutron Probe

- Contains slightly radioactive source of fast neutrons; thermalized neutrons are counted
- Poses negligible health hazard (IAEA)
- Calibration is linear – wet site-dry site
- Used mostly in research
- Accurate when calibrated
- Larger sensed volume than other sensors
- Used by consultants in high-value crops
- Not much used in production agriculture
- Highly regulated – requires safety training



Electromagnetic Sensors

- Time Domain
  - Conventional TDR --------- New, compact TDR
- Frequency Domain
  - Capacitance sensors
  - Essentially are Antennas
- Mixed Technologies
  - Quasi TDR, reflectometers…

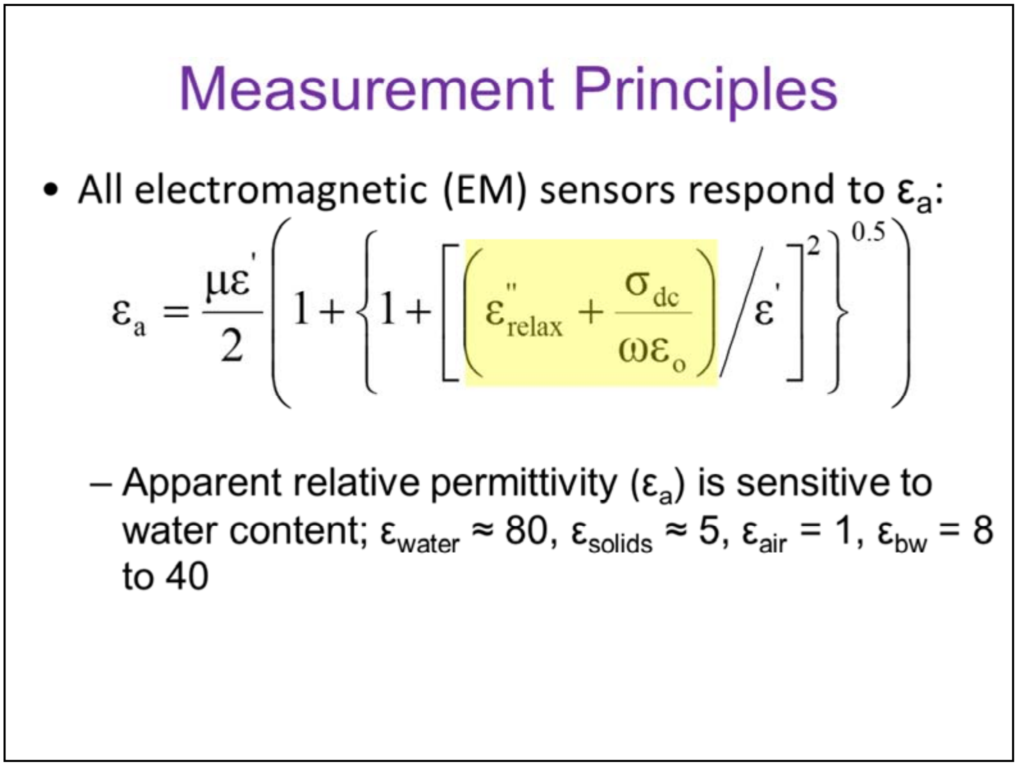
Electrode

Electrode

Access tube

From 2000 to 2005, the International Atomic Energy Agency (IAEA), Vienna, Austria, sponsored an international team of researchers to compare the neutron probe to capacitance and time domain reflectometry methods of soil water content sensing. The team published their results in a nine-chapter book (Evett et al., 2008) in which they concluded that the neutron probe and time domain reflectometry were the only sensor types accurate enough for determination of crop water use and irrigation scheduling by soil water balance. Sensors shown were compared, along with several others.

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen. 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. 131 pp. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801



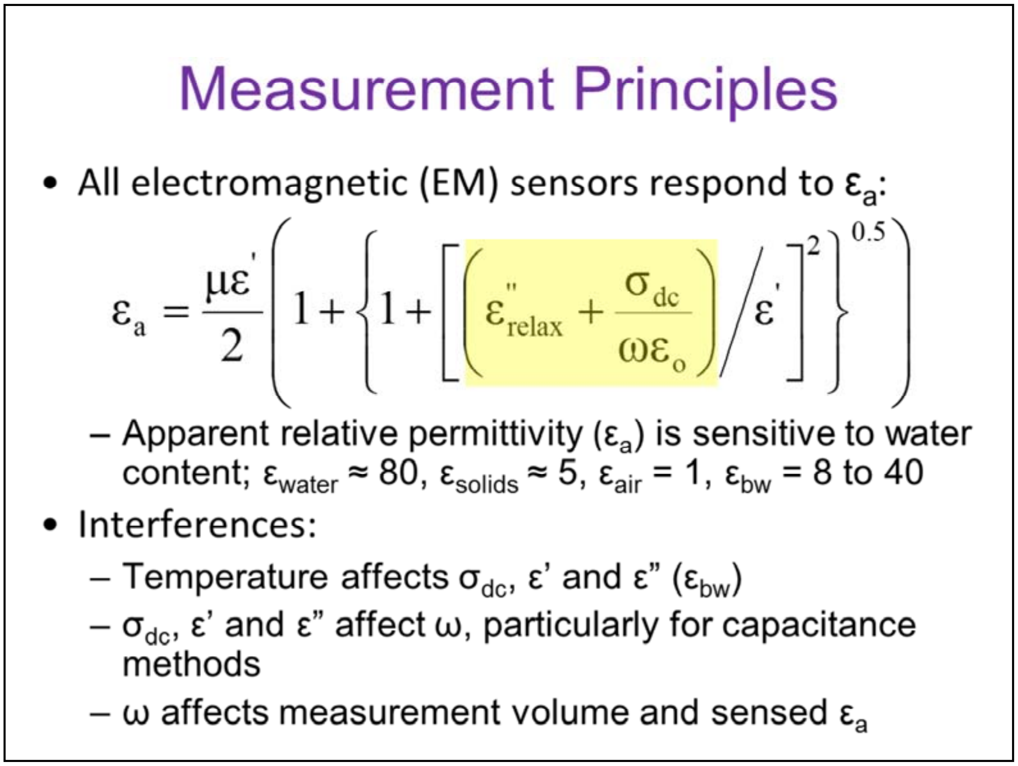
Measurement Principles

- All electromagnetic (EM) sensors respond to ε_a:

$$\varepsilon_a = \frac{\mu\varepsilon'}{2}\left(1+\left\{1+\left[\left(\varepsilon''_{relax}+\frac{\sigma_{dc}}{\omega\varepsilon_o}\right)\Big/\varepsilon'\right]^2\right\}^{0.5}\right)$$

  - Apparent relative permittivity (ε_a) is sensitive to water content; $\varepsilon_{water} \approx 80$, $\varepsilon_{solids} \approx 5$, $\varepsilon_{air} = 1$, $\varepsilon_{bw} = 8$ to 40

The frequency domain and time domain sensors are all electronic sensors that respond to the apparent relative permittivity of soil, ε_a. The equation from physics describing how ε_a is related to soil and sensor properties is shown. The water content is directly related to the real component of permittivity, ε', but sensors respond to ε_a, which is influenced by other soil and sensor properties. The relationship between water content and ε_a varies depending on the frequency of measurement, ω, a sensor property. Soil specific calibration of electromagnetic soil water content sensors is complicated by interacting interferences from soil bulk electrical conductivity (BEC), σ_{dc}, and temperature effects on real and imaginary components of permittivity. The sensors operating at lesser frequencies (typically capacitance, FD, sensors) allow the interference from bulk EC to become important due to the increase in the value of σ_{dc}/ω as ω decreases. The value of ε_0 is a constant, the permittivity of free space. The time domain sensors measure the travel time of an electronic pulse, not a frequency. Those so-called time domain sensors, sometimes called TDR, that measure a frequency are not true time domain sensors.



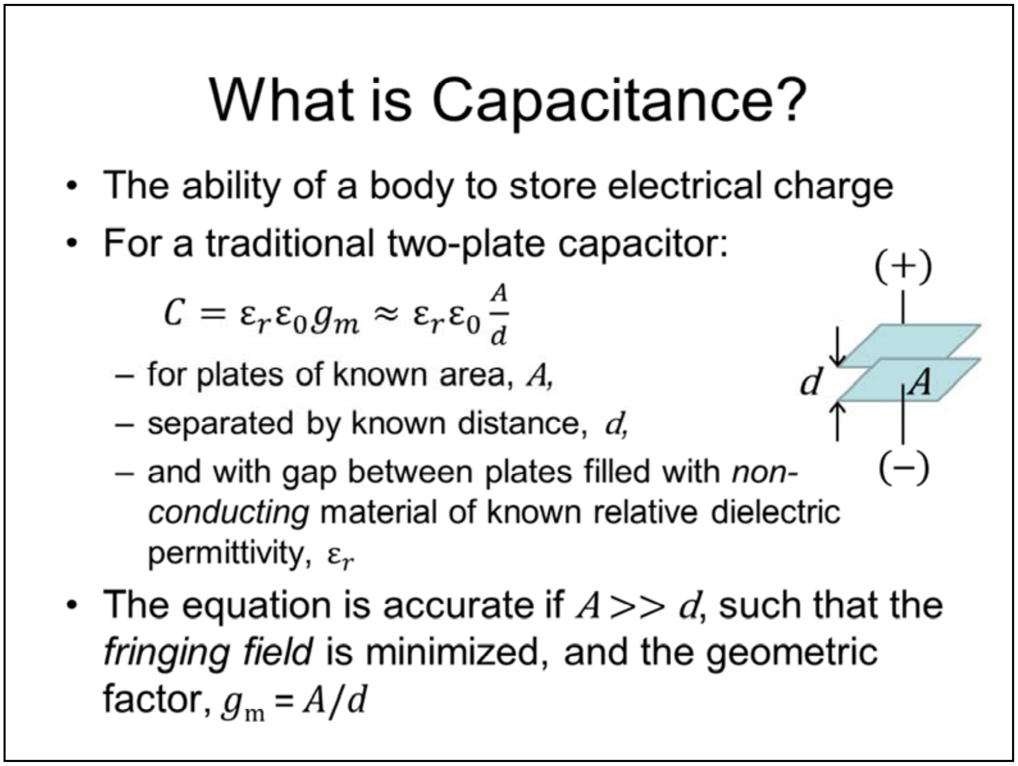
Measurement Principles

- All electromagnetic (EM) sensors respond to ε_a:

$$\varepsilon_a = \frac{\mu\varepsilon'}{2}\left(1+\left\{1+\left[\left(\varepsilon''_{relax}+\frac{\sigma_{dc}}{\omega\varepsilon_o}\right)\Big/\varepsilon'\right]^2\right\}^{0.5}\right)$$

  - Apparent relative permittivity (ε_a) is sensitive to water content; $\varepsilon_{water} \approx 80$, $\varepsilon_{solids} \approx 5$, $\varepsilon_{air} = 1$, $\varepsilon_{bw} = 8$ to 40
- Interferences:
  - Temperature affects σ_{dc}, ε' and ε" (ε_{bw})
  - σ_{dc}, ε' and ε" affect ω, particularly for capacitance methods
  - ω affects measurement volume and sensed ε_a

The frequency domain and time domain sensors are all electronic sensors that respond to the apparent relative permittivity of soil, ε_a. The equation from physics describing how ε_a is related to soil and sensor properties is shown. The water content is directly related to the real component of permittivity, ε', but sensors respond to ε_a, which is influenced by other soil and sensor properties. The relationship between water content and ε_a varies depending on the frequency of measurement, ω, a sensor property. Soil specific calibration of electromagnetic soil water content sensors is complicated by interacting interferences from soil bulk electrical conductivity (BEC), σ_{dc}, and temperature effects on real and imaginary components of permittivity. The sensors operating at lesser frequencies (typically capacitance, FD, sensors) allow the interference from bulk EC to become important due to the increase in the value of σ_{dc}/ω as ω decreases. The value of ε_0 is a constant, the permittivity of free space. The time domain sensors measure the travel time of an electronic pulse, not a frequency. Those so-called time domain sensors, sometimes called TDR, that measure a frequency are not true time domain sensors.



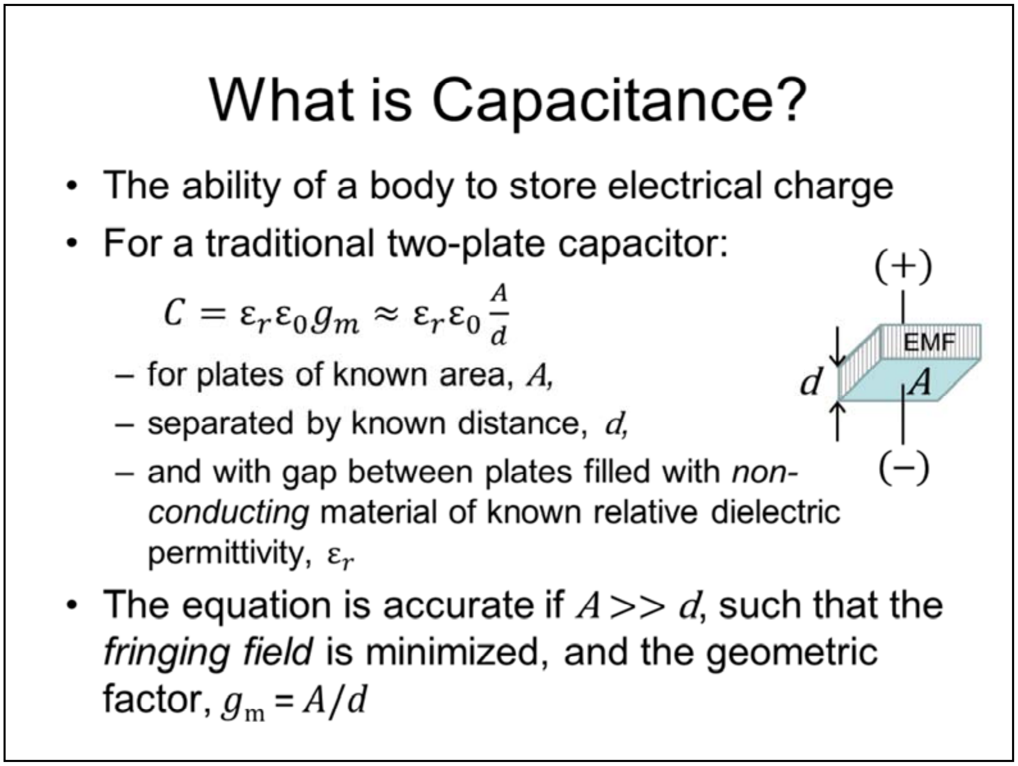
What is Capacitance?

- The ability of a body to store electrical charge
- For a traditional two-plate capacitor:

$$C = \varepsilon_r \varepsilon_0 g_m \approx \varepsilon_r \varepsilon_0 \frac{A}{d}$$

  - for plates of known area, A,
  - separated by known distance, d,
  - and with gap between plates filled with *non-conducting* material of known relative dielectric permittivity, ε_r
- The equation is accurate if $A >> d$, such that the *fringing field* is minimized, and the geometric factor, $g_{\mathrm{m}} = A/d$

The symbol ε_0 is the permittivity of free space, a constant.



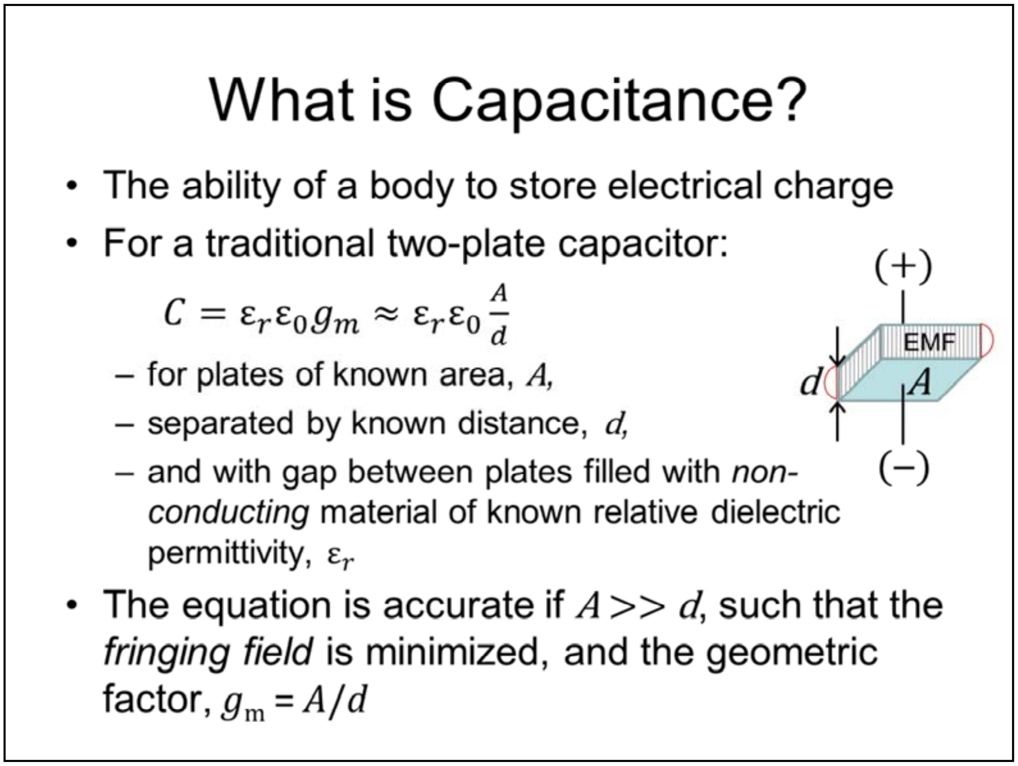
What is Capacitance?

- The ability of a body to store electrical charge
- For a traditional two-plate capacitor:

$$C = \varepsilon_r \varepsilon_0 g_m \approx \varepsilon_r \varepsilon_0 \frac{A}{d}$$

  - for plates of known area, A,
  - separated by known distance, d,
  - and with gap between plates filled with *non-conducting* material of known relative dielectric permittivity, ε_r
- The equation is accurate if $A >> d$, such that the *fringing field* is minimized, and the geometric factor, $g_\mathrm{m} = A/d$

The symbol ε_0 is the permittivity of free space, a constant.



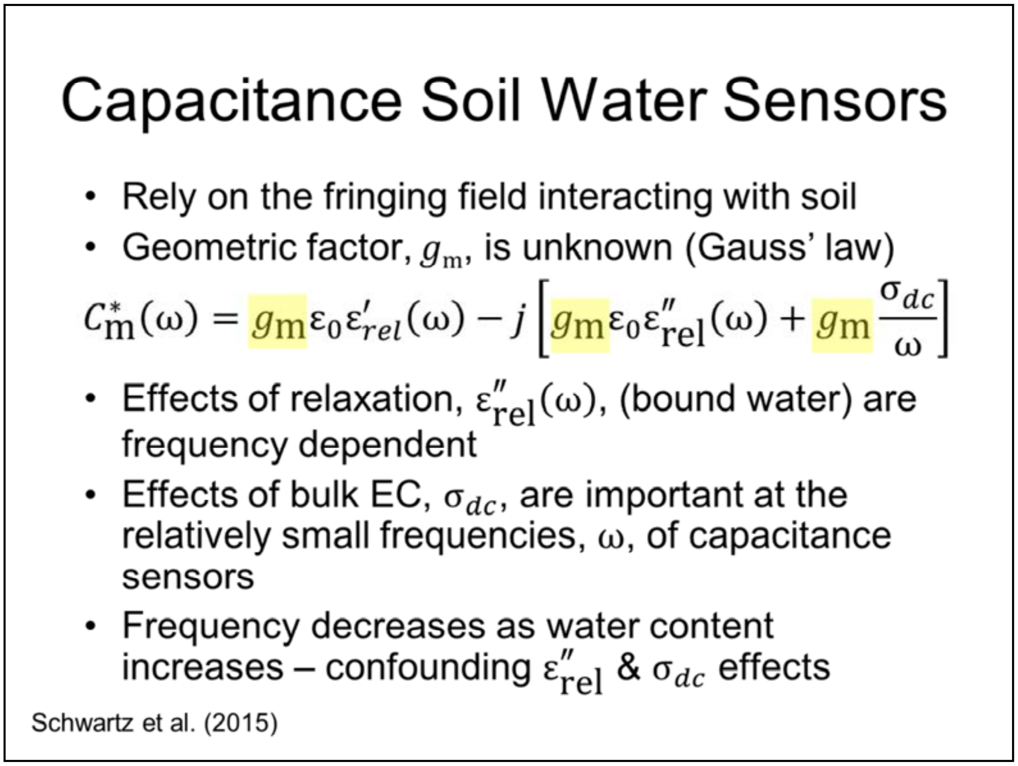
What is Capacitance?

- The ability of a body to store electrical charge
- For a traditional two-plate capacitor:

$$C = \varepsilon_r \varepsilon_0 g_m \approx \varepsilon_r \varepsilon_0 \frac{A}{d}$$

  - for plates of known area, A,
  - separated by known distance, d,
  - and with gap between plates filled with *non-conducting* material of known relative dielectric permittivity, ε_r
- The equation is accurate if $A >> d$, such that the *fringing field* is minimized, and the geometric factor, $g_\mathrm{m} = A/d$

The symbol ε_0 is the permittivity of free space, a constant.



Capacitance Soil Water Sensors

- Rely on the fringing field interacting with soil
- Geometric factor, g_{m}, is unknown (Gauss' law)

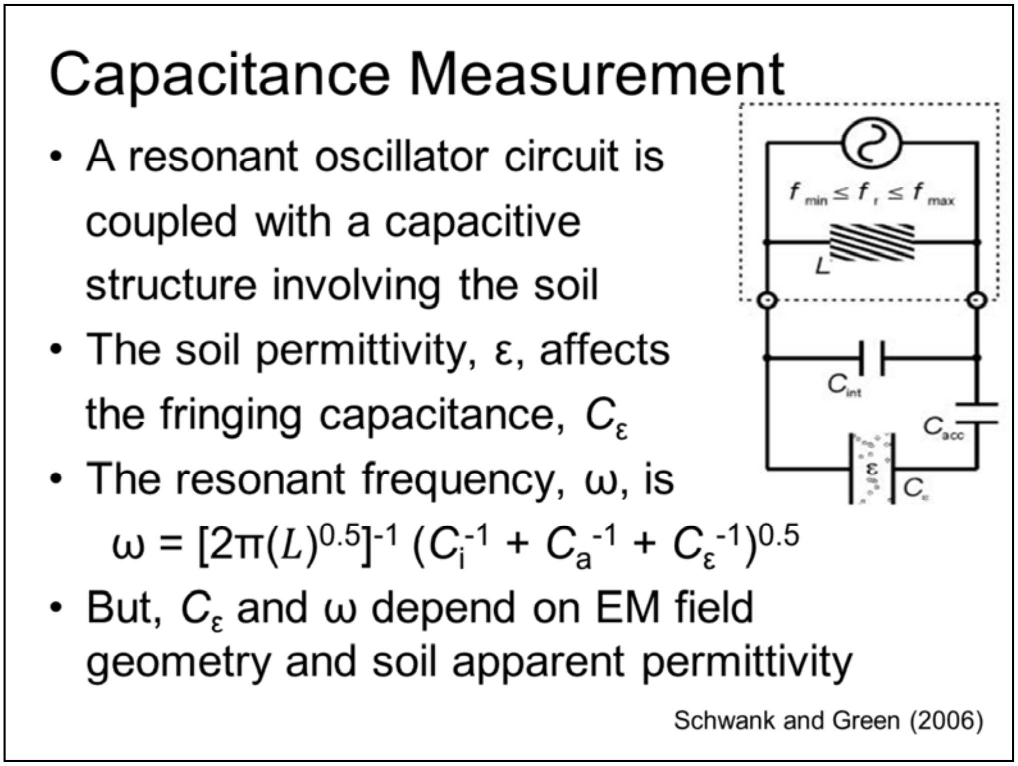
$$C^*_{\mathrm{m}}(\omega) = g_{\mathrm{m}}\varepsilon_0\varepsilon'_{rel}(\omega) - j\left[g_{\mathrm{m}}\varepsilon_0\varepsilon''_{\mathrm{rel}}(\omega) + g_{\mathrm{m}}\frac{\sigma_{dc}}{\omega}\right]$$

- Effects of relaxation, $\varepsilon''_{\mathrm{rel}}(\omega)$, (bound water) are frequency dependent
- Effects of bulk EC, σ_{dc}, are important at the relatively small frequencies, ω, of capacitance sensors
- Frequency decreases as water content increases – confounding $\varepsilon''_{\mathrm{rel}}$ & σ_{dc} effects

Schwartz et al. (2015)

In contrast with a capacitor designed for electronic circuits, which are designed to minimize the fringing field, capacitance sensors for soil water sensing rely on the fringing field interacting with the soil. Gauss' law is the physical equation describing the complex physical interactions that determine the frequency dependent capacitance, $C^*_{\mathrm{m}}(\omega)$, in such a system. The value of the geometric factor, g_{m}, is unknown, and it affects the value of every part of the equation. The loss tangent, σ_{dc}/ω, becomes an important effect when soil bulk EC, σ_{dc} , is appreciable since the value of ω is relatively small and becomes smaller as water content increases.

Schwartz, R.C., S.R. Evett, S. Anderson and D. Anderson. Evaluation of a direct-coupled TDR for determination of soil water content and bulk electrical conductivity. Submitted to Vadose Zone Journal, 24 August 2015. Accepted 11 Nov 2015. doi: 10.2136/vzj2015.08.0115



Capacitance Measurement

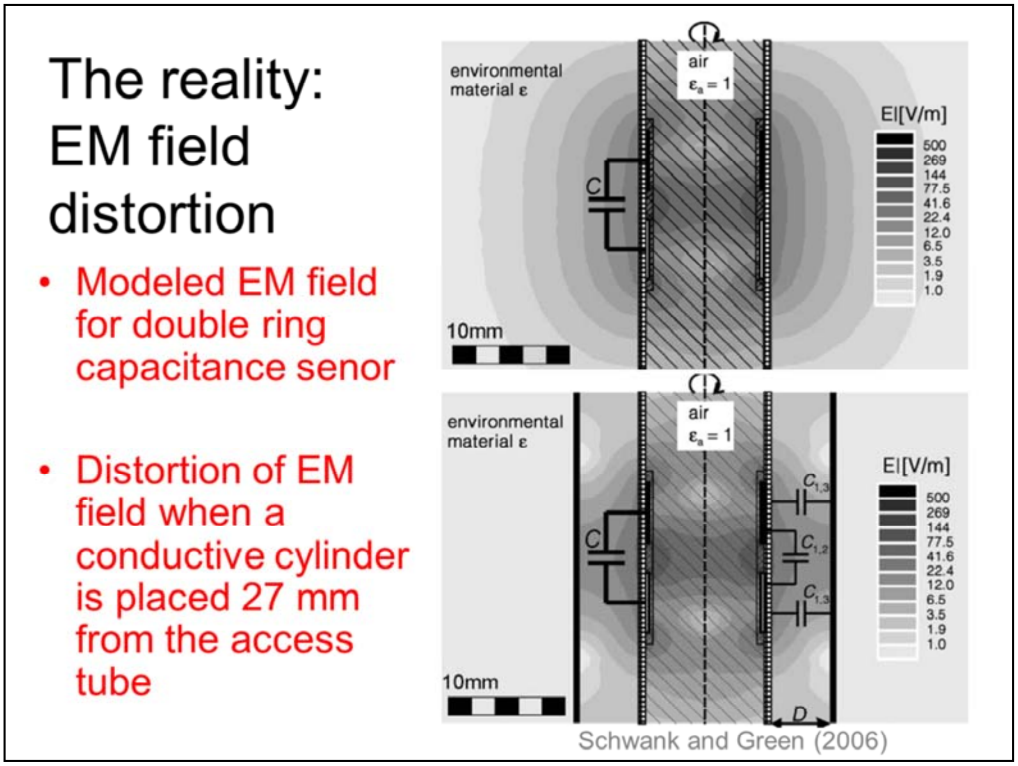
- A resonant oscillator circuit is coupled with a capacitive structure involving the soil
- The soil permittivity, ε, affects the fringing capacitance, C_ε
- The resonant frequency, ω, is

  $\omega = [2\pi(L)^{0.5}]^{-1} (C_i^{-1} + C_a^{-1} + C_\varepsilon^{-1})^{0.5}$
- But, C_ε and ω depend on EM field geometry and soil apparent permittivity

Schwank and Green (2006)

The frequency domain sensors involve sensing the resonant frequency of an oscillator circuit, one capacitor of which is set up such that its electromagnetic field (EMF) partially passes through the soil as shown in the diagram. In the equation describing the resonant frequency, ω, the symbols C_i and C_a are the the capacitances of internal circuit elements to which the electrodes are connected, C_ε is the capacitance of the soil/access tube system, and L is the inductance (Henries) of the coil in the oscillator circuit. A key point is that the capacitance of the system and thus its resonant frequency, ω, are dependent on the value of the geometric constant, g, since $C = g\varepsilon_a$. If g changes then C and ω change, even if mean water content remains the same.

Schwank, M., T.R. Green, C. Mätzler, H. Benedickter, and H. Flühler. 2006. Laboratory characterization of a commercial capacitance sensor for estimating permittivity and inferring soil water content. Vadose Zone J. 5:1048–1064.



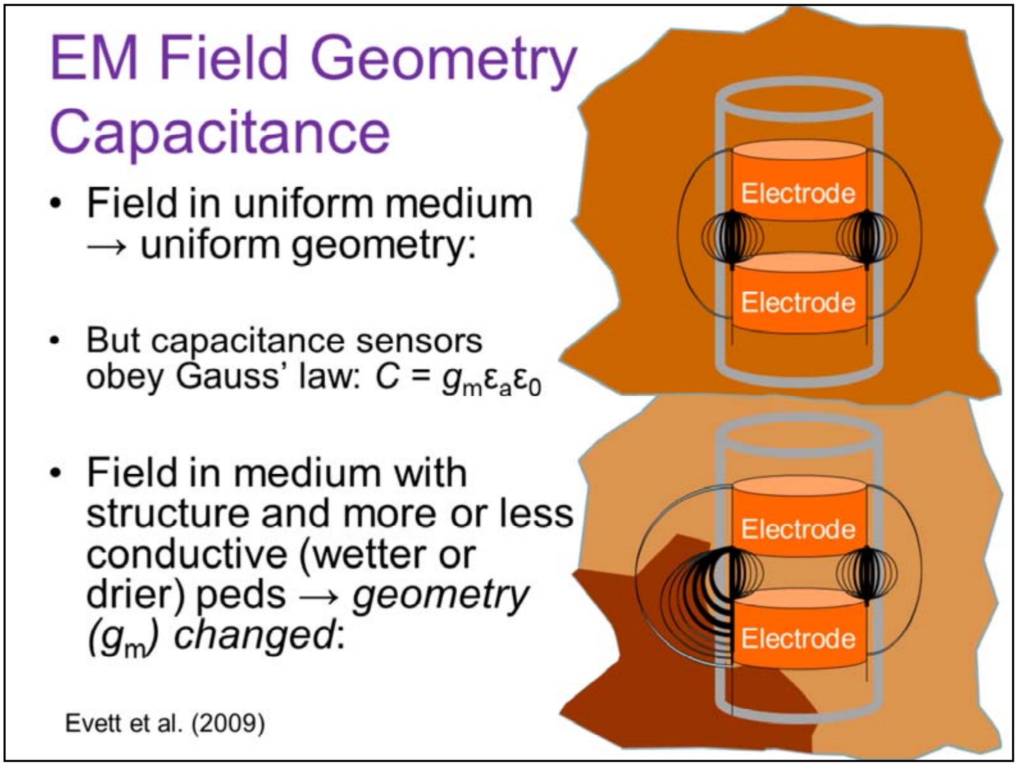
The reality: EM field distortion

- Modeled EM field for double ring capacitance senor
- Distortion of EM field when a conductive cylinder is placed 27 mm from the access tube

Schwank and Green (2006)

Schwank et al. (2006) found that a conductor placed next to the plastic access tube of a capacitance sensor (EnviroSCAN in this case) caused the electromagnetic (EM) field to be drawn to the conductor, resulting in a change in the geometric constant. This result is consistent with EM theory and experimentation in many fields of study, including the field of antenna design. Since soils exhibit large small-scale variation in water content, bulk density and bulk electrical conductivity, we can expect the fringing field from capacitance sensors will be drawn to the more conductive peds, which are arranged differently around the access tube at every depth and tube location.

Schwank, M., T.R. Green, C. Mätzler, H. Benedickter, and H. Flühler. 2006. Laboratory characterization of a commercial capacitance sensor for estimating permittivity and inferring soil water content. Vadose Zone J. 5:1048–1064.



EM Field Geometry Capacitance

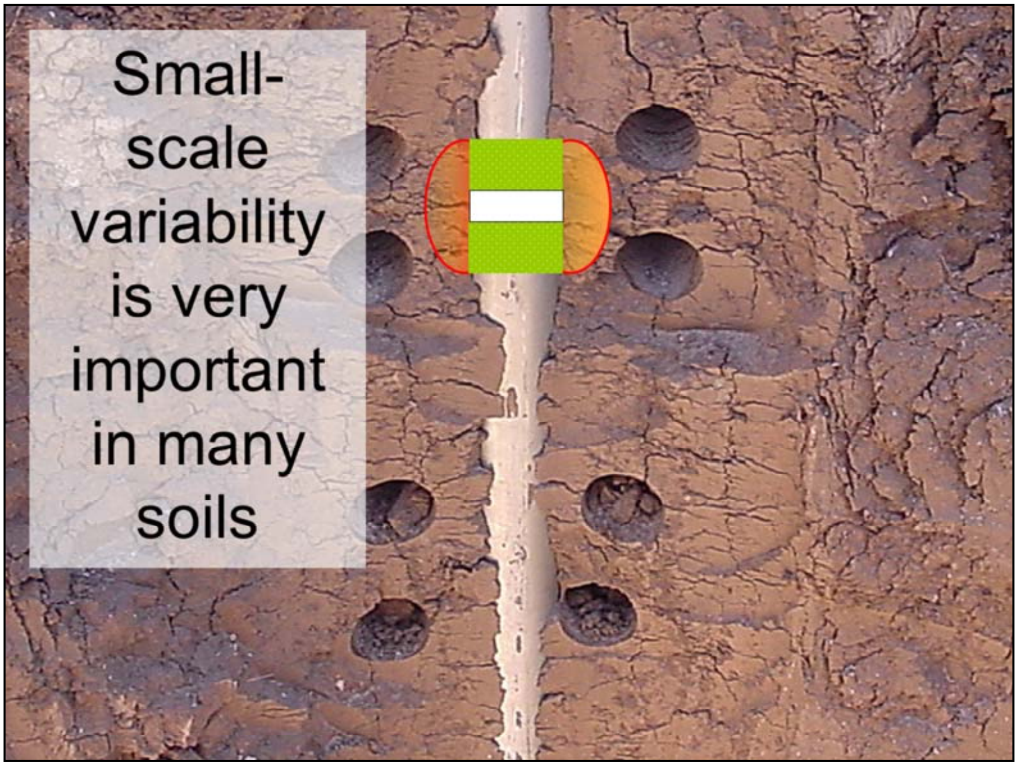
- Field in uniform medium → uniform geometry:
- But capacitance sensors obey Gauss' law: $C = g_m \varepsilon_a \varepsilon_0$
- Field in medium with structure and more or less conductive (wetter or drier) peds → *geometry* (g_m) *changed*:

Evett et al. (2009)

Evett et al. (2009) and Evett and Steiner (1995) demonstrated that capacitance sensors responded reproducibly and with high correlation between sensors to the soil state at each depth in each access tube (minimum of six access tubes), but that the correlation between the sensor readings and the soil volumetric water content at each depth at each access tube was very poor. Drawing from studies of EM field penetration in heterogeneous materials that showed overestimation of permittivity and uneven EM field penetration in those materials, they inferred that the EM field from a capacitance sensor is distorted by the individual arrangement of soil peds and pattern of water content in the peds around each access tube at each depth, rather than being responsive to the mean water content of the soil around each access tube at each depth. This means that the geometric constant changes with the small scale heterogeneity of soil properties at each measurement depth and access tube, which results in a different resonant frequency and water content estimate even if mean water content around the access tube is the same.

Evett, S.R., R.C. Schwartz, J.A. Tolk, and T.A. Howell. 2009. Soil profile water content determination: Spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes. Vadose Zone J. 8(4):926-941.

Evett, S. R. and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59(4):961-968.

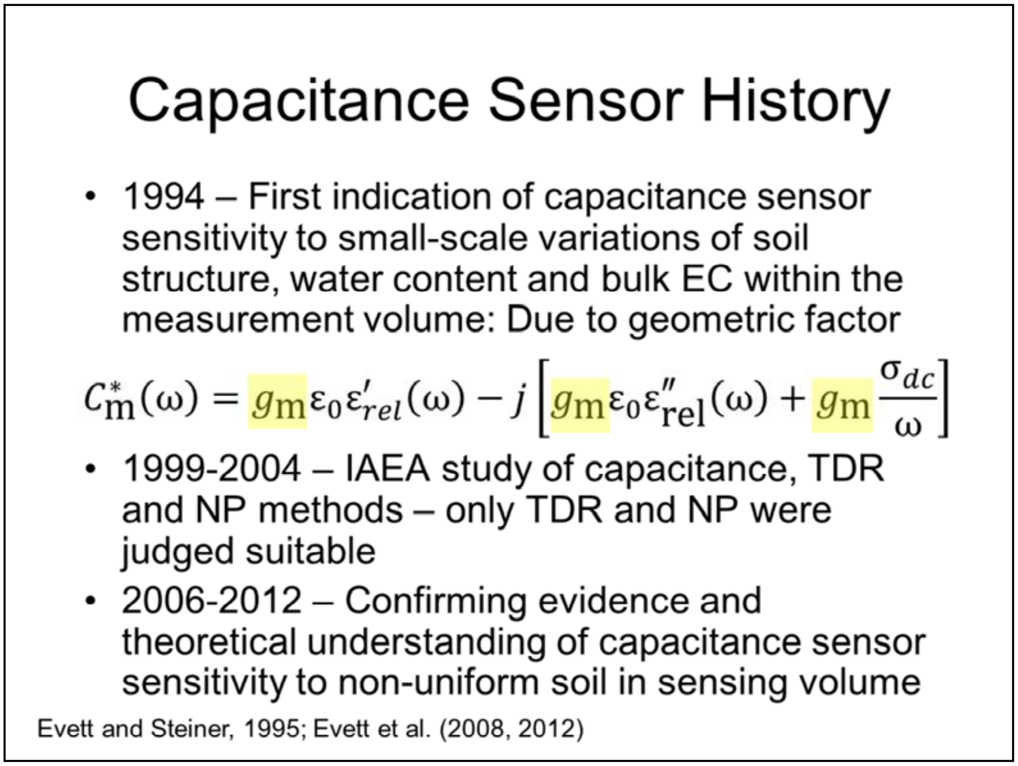


Small-scale variability is very important in many soils

The Pullman soil series has a Bt horizon with ~50% clay, which cracks on drying. Soil structure is strongly expressed. Overlain on the photograph is a cross section of the 90% sampling volume of a capacitance sensors (EnviroSCAN) at its largest extent as determined by measurements made by Evett et al. (2006) and Paltineanu and Starr (1997). Many individual soil peds are contained within that volume, which can lead to bias in measurement since the field will not uniformly interrogate the volume if there are differences in water content within and among the peds, which is likely.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2006. Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence, and precision. Vadose Zone J. 5:894–907.

Paltineanu, I.C., and J.L. Starr. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61:1576–1585.



Capacitance Sensor History

- 1994 – First indication of capacitance sensor sensitivity to small-scale variations of soil structure, water content and bulk EC within the measurement volume: Due to geometric factor

$$C^*_{\mathrm{m}}(\omega) = g_{\mathrm{m}}\varepsilon_0\varepsilon'_{rel}(\omega) - j\left[g_{\mathrm{m}}\varepsilon_0\varepsilon''_{\mathrm{rel}}(\omega) + g_{\mathrm{m}}\frac{\sigma_{dc}}{\omega}\right]$$

- 1999-2004 – IAEA study of capacitance, TDR and NP methods – only TDR and NP were judged suitable
- 2006-2012 – Confirming evidence and theoretical understanding of capacitance sensor sensitivity to non-uniform soil in sensing volume

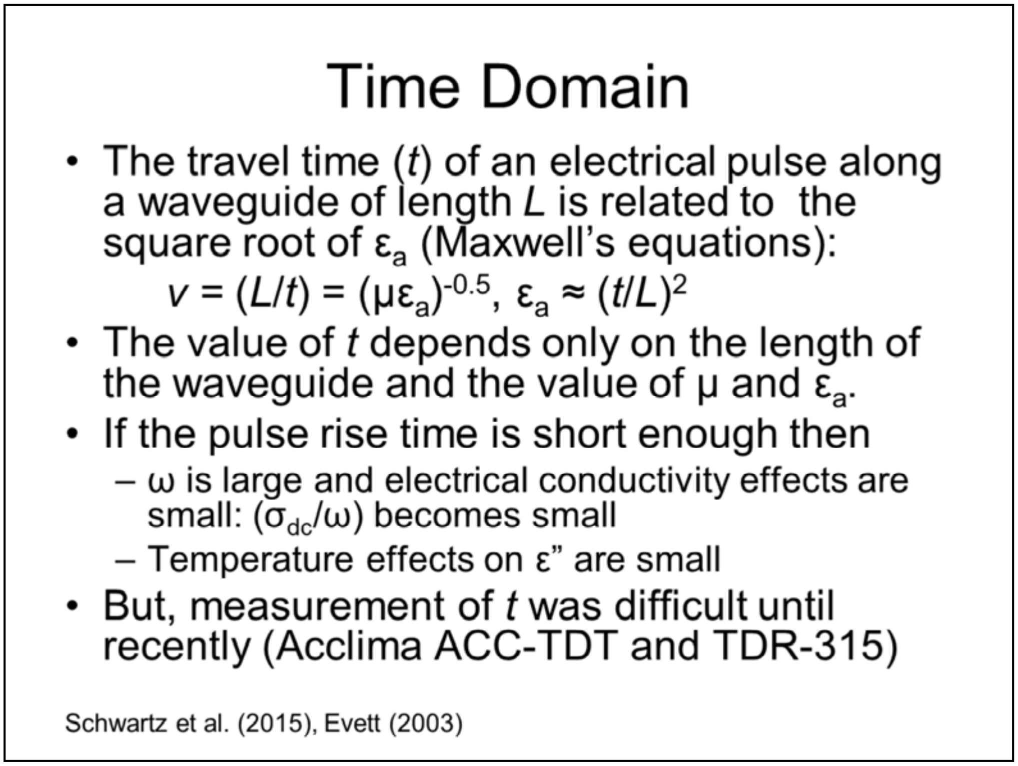
Evett and Steiner, 1995; Evett et al. (2008, 2012)

Evidence of the geometric factor influence on capacitance type sensor water content readings mounted steadily beginning in 1994 as reported by Evett and Steiner (1995). The five-year international study sponsored by the International Atomic Energy Agency/FAO Joint Soils Division provided additional evidence of these problems in soils in several countries (Evett et al., 2008). Laboratory and field studies confirmed the evidence for the influence of the geometric factor and increased theoretical understanding of the problem, culminating in a paper summarizing the results (Evett et al., 2012).

Evett, S.R. and J.L. Steiner. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59(4):961-968.

Evett, S.R., R.C. Schwartz, J.J. Casanova, and L.K. Heng. 2012. Soil water sensing for water balance, ET and WUE. Agric. Water Manage. 104:1-9. http://dx.doi.org/10.1016/j.advwatres.2012.07.009

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.). 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518.



Time Domain

- The travel time (t) of an electrical pulse along a waveguide of length L is related to the square root of ε_a (Maxwell's equations):

  $$v = (L/t) = (\mu\varepsilon_a)^{-0.5},\ \varepsilon_a \approx (t/L)^2$$

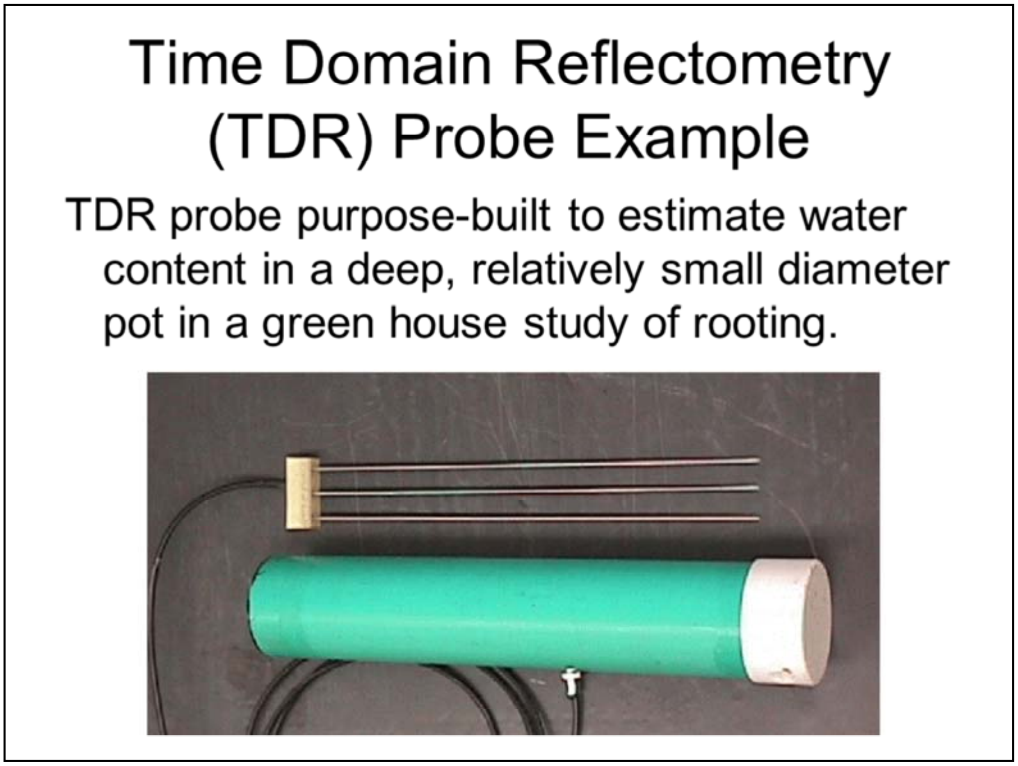
- The value of t depends only on the length of the waveguide and the value of μ and ε_a.
- If the pulse rise time is short enough then
  - ω is large and electrical conductivity effects are small: (σ_{dc}/ω) becomes small
  - Temperature effects on ε" are small
- But, measurement of t was difficult until recently (Acclima ACC-TDT and TDR-315)

Schwartz et al. (2015), Evett (2003)

Time domain sensors measure the travel time of an electronic pulse that is sent through electrodes (usually stainless steel rods, often called a waveguide) in the soil. They do not measure a capacitance and are not influenced by the geometric constant. They operate according to Maxwell's equations, not Gauss' equations. The travel time measurement is thus not related to the degree of penetration of the electromagnetic field into the soil. So, time domain sensors are much less influenced by soil small scale variability than are capacitance (FD) sensors. True time domain sensors have been very expensive in the past, which is why they have not been much used other than in agricultural and environmental science. The relatively inexpensive ($100's) sensors that were purported to be TDR sensors in the past, were not true time domain sensors. New, relatively inexpensive true time domain sensors are now available in the market (Acclima TDR-315 and ACC-TDT). Travel time sensors provided an integrated response to soil permittivity along the length of the sensor electrodes (waveguide) and true average water content along that length. The magnetic permeability, μ, is assumed equal to unity, which it is for many soils; for the few soils for which μ ≠ 1, the value of μ can be found.

Schwartz, R.C., S.R. Evett, S. Anderson and D. Anderson. 2015,. Evaluation of a direct-coupled TDR for determination of soil water content and bulk electrical conductivity. Vadose Zone J. doi: 10.2136/vzj2015.08.0115

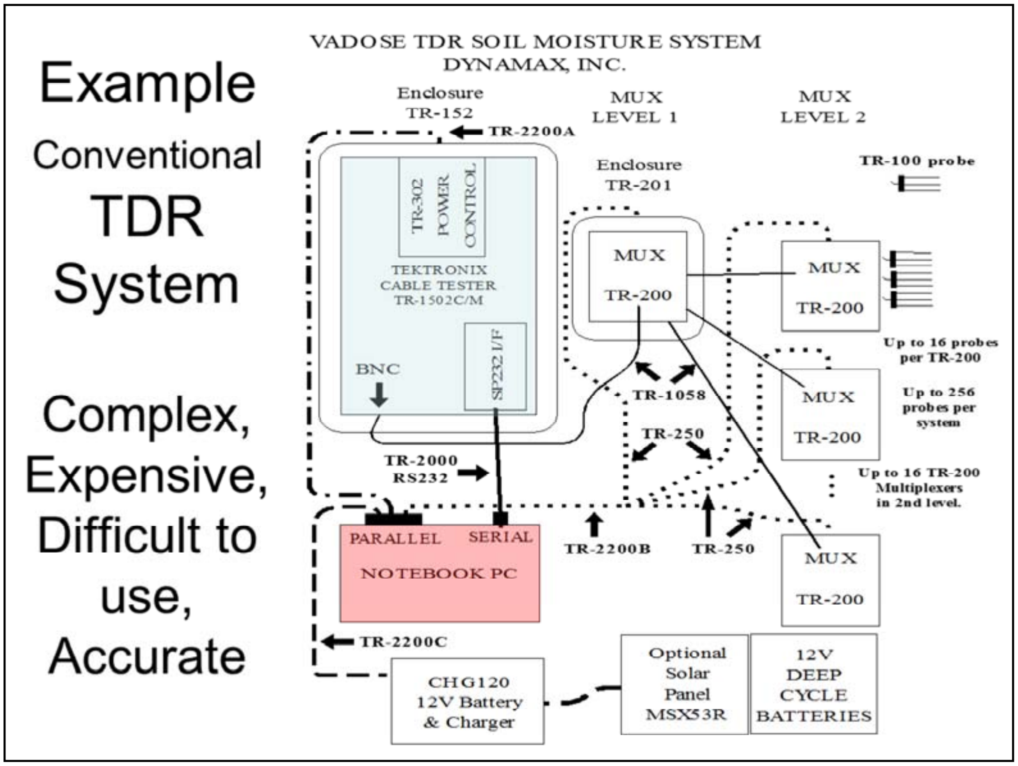
Evett, S.R. 2003. Measuring soil water by time domain reflectometry. In B.A. Stewart and Terry A. Howell (editors). Encyclopedia of Water Science, Marcel Dekker, Inc. New York. Pp. 894-898.



Time Domain Reflectometry (TDR) Probe Example

TDR probe purpose-built to estimate water content in a deep, relatively small diameter pot in a green house study of rooting.

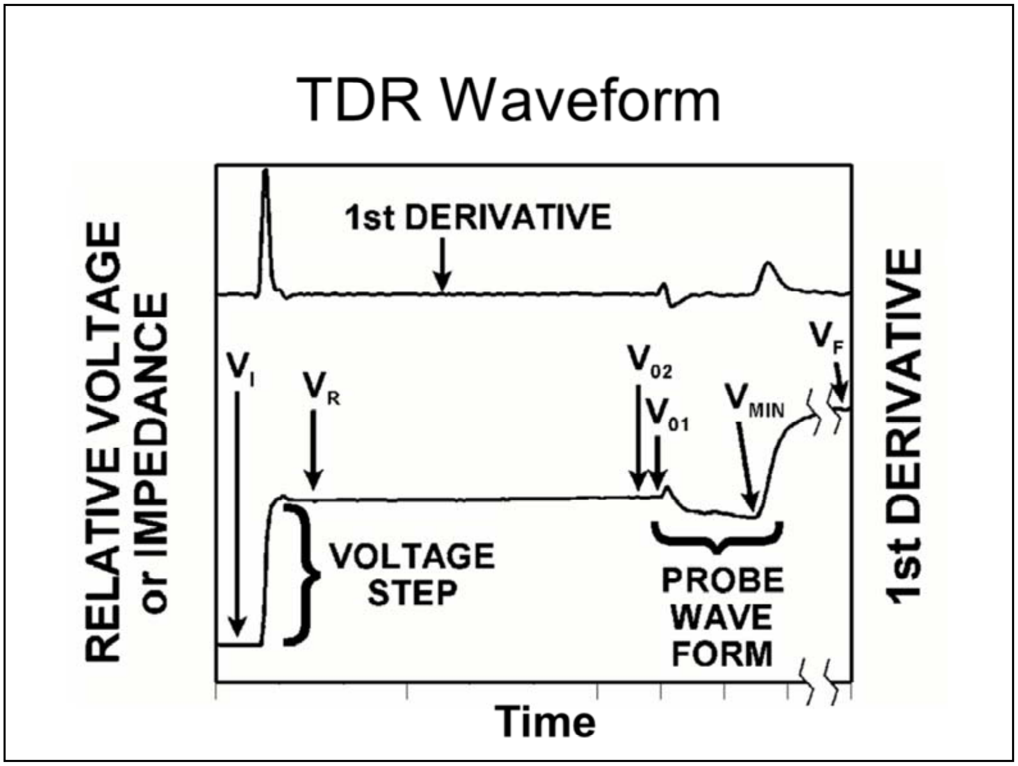
The TDR probe illustrated here was purpose-built to match the dimensions of the plastic pots used in a greenhouse study of rooting. The rod spacing is 2.5 cm center-to-center and the length is 34 cm. Probe constructed at the USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas USA. One of the advantages of the TDR method is the wide range of probe dimensions that may be used; lengths from 0.05 m to 1.5 m, have been used.



Example Conventional TDR System

Complex, Expensive, Difficult to use, Accurate

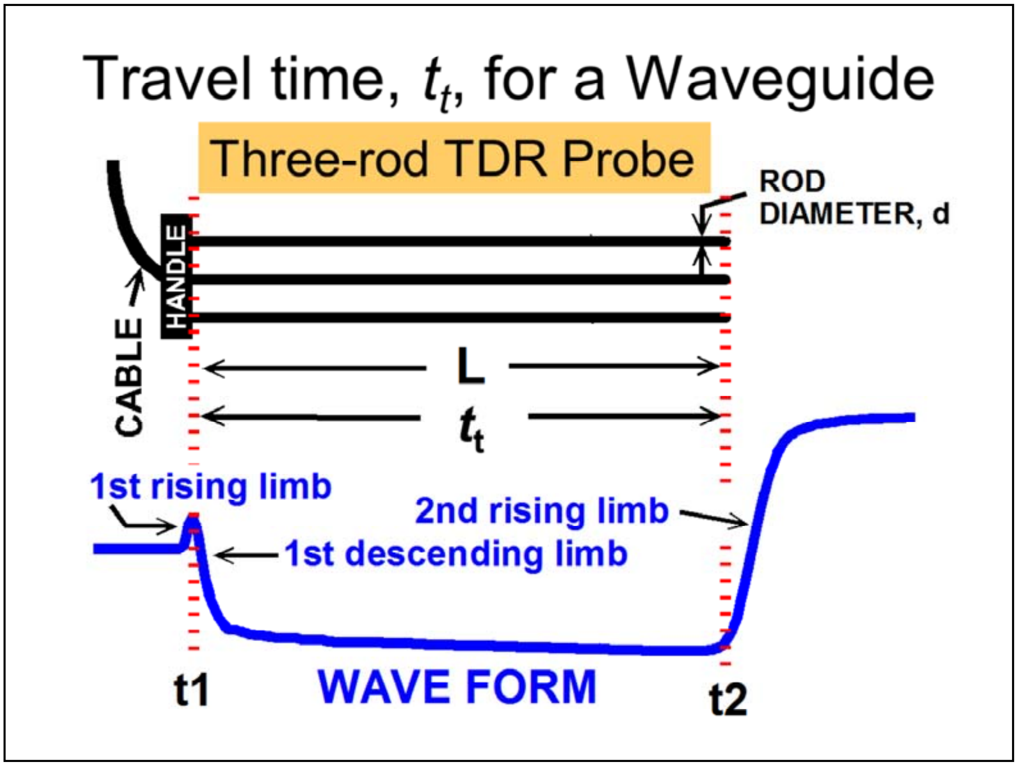
The example illustrated here is of the TDR system designed for Dynamax, Inc. through a Cooperative Research and Development Agreement with USDA-ARS, Conservation & Production Research Laboratory, Bushland, Texas USA. The multiplexers and TDR probes were designed by Evett (1998) as was the TACQ software that runs on a PC/AT compatible computer to control and acquire data from the system (Evett, 2000ab). This is an example of a conventional TDR system. Campbell Scientific, Inc. sells the TDR-100 instrument that is similar in function to the Tektronix 1502C shown here. Soil Moisture, Inc. sells the Trace TDR system, which is similar in function and complexity to what is shown here. Complex systems such as the one shown are used in research, but are too complicated for routine use in water management.



TDR Waveform

The TDR waveform is a record of reflected voltage versus time. Shown here is the waveform captured by a Tektronix 1502C TDR instrument (cable tester) beginning inside the instrument itself where the fast rise time (150 ps) voltage step is injected into the coaxial conductor. In the coaxial cable that connects the TDR instrument to the TDR probe, the reflected voltage remains relatively constant at the value of the voltage step. At the head of the TDR probe, the voltage reflected peaks due to the connection of the coaxial cable to the probe electrodes. As the step pulse travels along the probe electrodes (waveguide), the voltage declines in this example due to conductance through the soil between the electrodes (this does not affect the travel time). At the end of the probe electrodes, the step pulse is reflected due to the electrodes constituting an open circuit. For explanation of the voltage values illustrated, see Evett (2003).

Evett, S.R. 2003. Measuring soil water by time domain reflectometry. In B.A. Stewart and Terry A. Howell (editors). Encyclopedia of Water Science, Marcel Dekker, Inc. New York. Pp. 894-898.

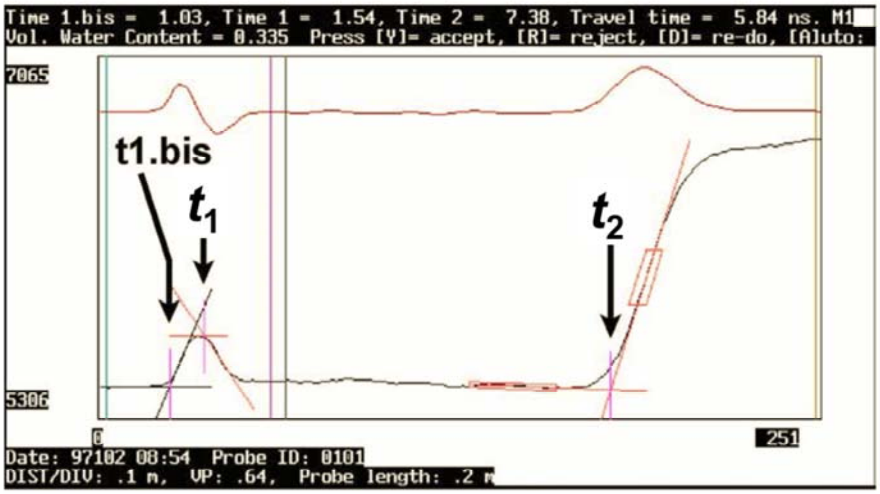


Travel time, t_t, for a Waveguide

Shown here is the relationship between trifilar (three-electrode) TDR probe and its waveform. Each point along the waveform corresponds to a particular distance along the waveguide, where distance from the signal source increases from left to right. The height of the waveform is related to the impedance of the waveguide at the corresponding point along the waveguide. The first peak is caused by the separation of the coaxial cable outer conductor from its inner one in the probe handle. The descent of the waveform after the 1st peak is due to the water content of the soil, which lowers the impedance of the waveguide in the soil. The 2nd rising limb is due to the reflection of the pulse energy at the ends of the waveguide (probe rods).

Although each point along the waveform is related to distance from the signal source, the relationship is not uniform but is determined by the propagation velocity of the TDR signal, which varies as the medium around the waveguide varies (ie., as water content varies). The horizontal axis of a waveform acquired by a TDR device is actually time, rather than distance. In the TDR method, we determine the pulse travel time along the part of the rods that is buried in the porous medium being assessed. This travel time represents the mean water content along the probe electrodes.

TDR Waveform Analysis; $t_t = t_2 - t_1$



```
Time 1.bis =  1.03, Time 1 =  1.54, Time 2 =  7.38, Travel time =  5.84 ns. M1
Vol. Water Content = 0.335  Press [Y]= accept, [R]= reject, [D]= re-do, [A]uto:
```

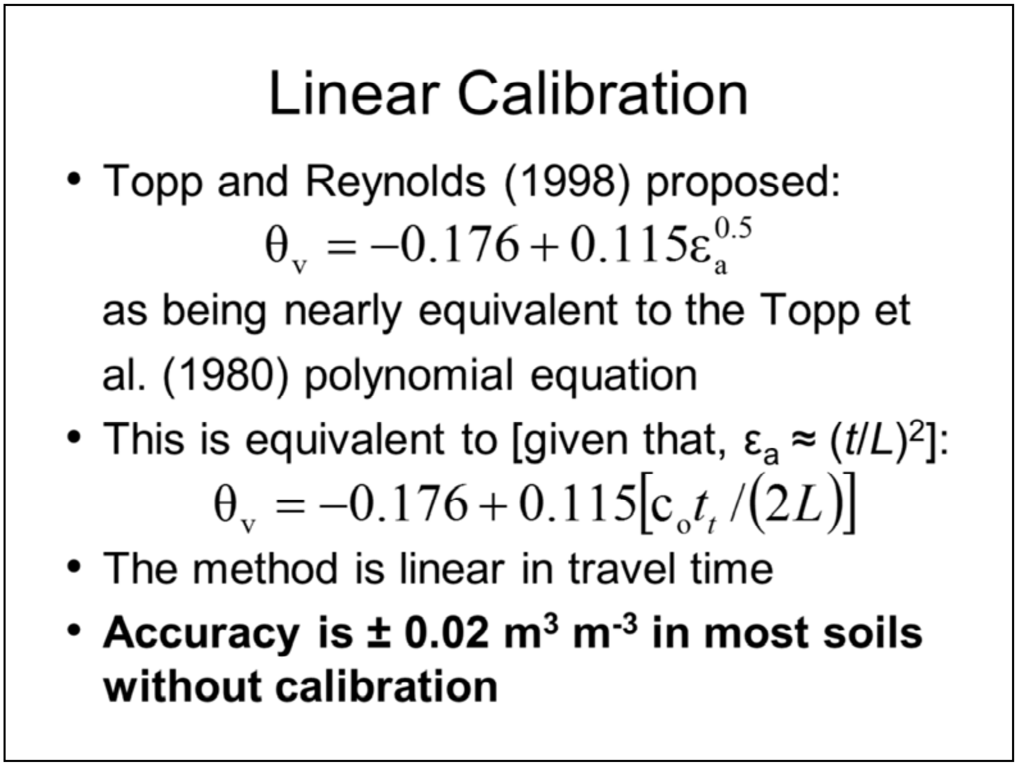
```
Date: 97102 08:54  Probe ID: 0101
DIST/DIV: .1 m,  VP: .64,  Probe length: .2 m
```

Evett (2000a,b), TACQ TDR SCADA computer program

In the earliest attempts to use TDR to assess soil water content, a photograph of the oscilloscope screen showing the waveform was taken. Tangent lines were drawn on the photograph, and the times t2 and t1 were determined by intersection of the tangent lines. The distance between these was proportional to the travel time, which was calculated according to the TDR instrument settings of propagation velocity and distance per division along the X-axis of the oscilloscope screen. This tedious process was computerized beginning in the late 1980s, and by 2000, the computer algorithms for determining travel time automatically were very capable as shown in this screen shot from the TACQ program (Evett, 2000).

Evett, S.R. 2000a. The TACQ Program for Automatic Time Domain Reflectometry Measurements: I. Design and Operating Characteristics. Trans. ASAE vol. 43(6):1939-1946.

Evett, S.R. 2000b. The TACQ Program for Automatic Time Domain Reflectometry Measurements: II. Waveform Interpretation Methods. Trans. ASAE vol. 43(6):1947-1956.



Linear Calibration

- Topp and Reynolds (1998) proposed:

$$\theta_v = -0.176 + 0.115\varepsilon_a^{0.5}$$

  as being nearly equivalent to the Topp et al. (1980) polynomial equation
- This is equivalent to [given that, $\varepsilon_a \approx (t/L)^2$]:

$$\theta_v = -0.176 + 0.115\left[c_o t_t/(2L)\right]$$

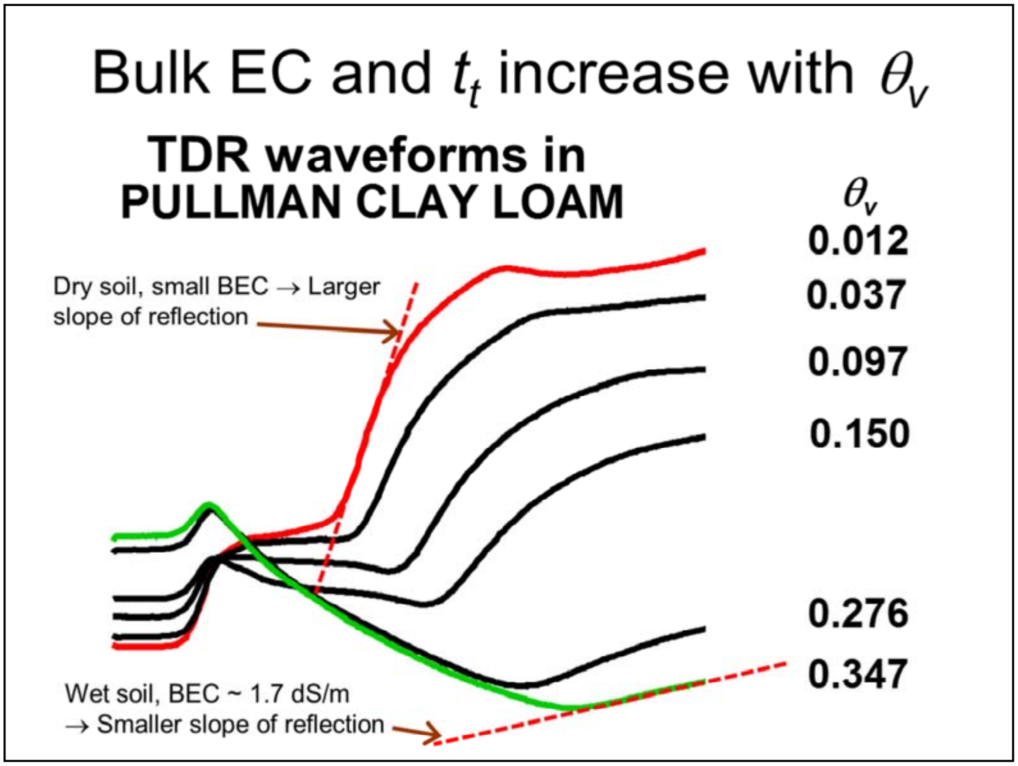
- The method is linear in travel time
- **Accuracy is ± 0.02 m^3 m^{-3} in most soils without calibration**

Calibrations for the TDR method are linear in terms of the measured quantity, which is the travel time, t_t. This raises the possibility of obtaining a calibration from only a few samples, some from wet soil and some from dry soil. In this way the TDR method is similar to the neutron thermalization method; and in this way both methods are superior to the frequency domain methods for which calibration equations are polynomial functions of the frequency or relative frequency shift. The linearity follows from the fact that $\varepsilon_a = [c_o t_t/(2L)]^2$, where c_o is the speed of light in a vacuum, a constant.

Topp, G.C., and W.D. Reynolds. Time domain reflectometry: A seminal technique for measuring mass and energy in soil. Soil Tillage Res. Vol. 47. Pp. 125-132. 1998.

Issues with Travel Time Methods

- Conventional TDR systems are complex and expensive
- Some “TDR” sensors are not TDR
- Incorrect travel time measurement methods, e.g. water content reflectometers
- Frequency Domain Reflectometry (FDR) is an example of incorrect travel time measurement – It’s more similar to a frequency domain method



Bulk EC and t_t increase with θ_v

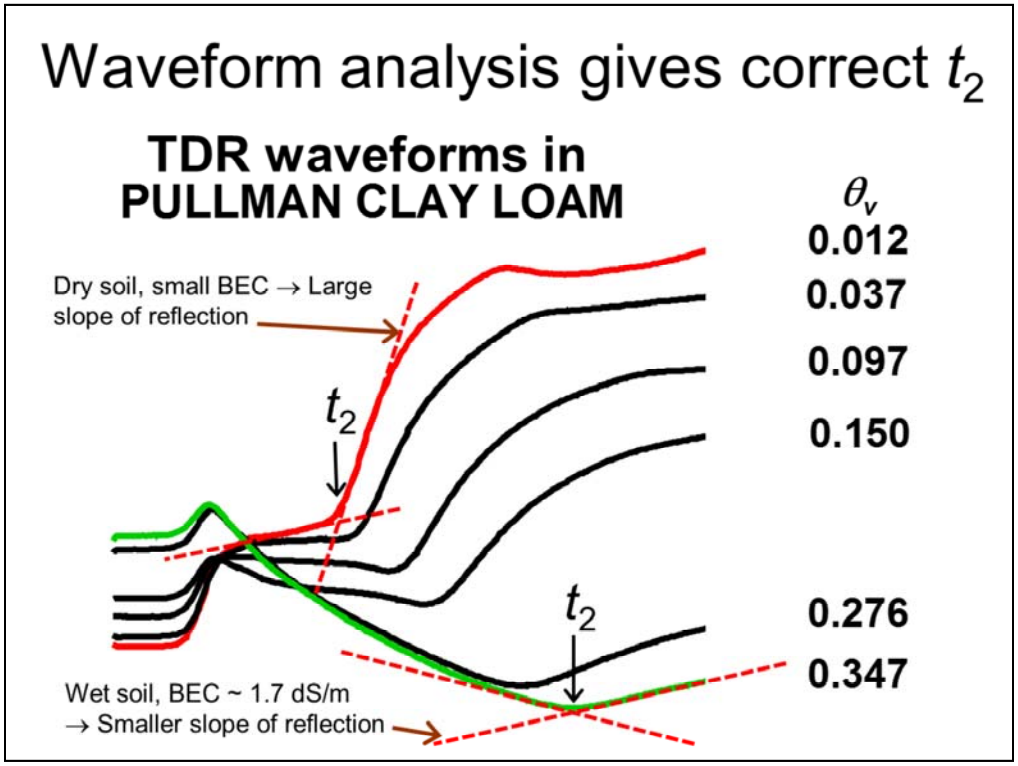
TDR waveforms in PULLMAN CLAY LOAM

Dry soil, small BEC → Larger slope of reflection

Wet soil, BEC ~ 1.7 dS/m → Smaller slope of reflection

While increasing water content would cause an increase in ε and thus a decrease in reflected voltage, the decrease in reflected voltage of the waveform illustrated here for wet Pullman clay loam (green line) is not completely explained by water content increase. The lack of a strong reflection at the end of the probe rods in the wet soil indicates that bulk electrical conductivity (BEC) has increased as the soil wetted. With correct waveform interpretation algorithms, the travel time can still be determined accurately (Schwartz et al., 2013). Most inexpensive and some expensive sensors that claim to be based on TDR do not, however, correctly determine the travel time with consequences in inaccuracy illustrated in the next slide.

Schwartz, R.C., J.J. Casanova, J.M. Bell, and S.R. Evett. 2013. A reevaluation of time domain reflectometry propagation time determination in soils. Vadose Zone J. doi:10.2136/vzj2013.07.0135.



Waveform analysis gives correct t_2

TDR waveforms in PULLMAN CLAY LOAM

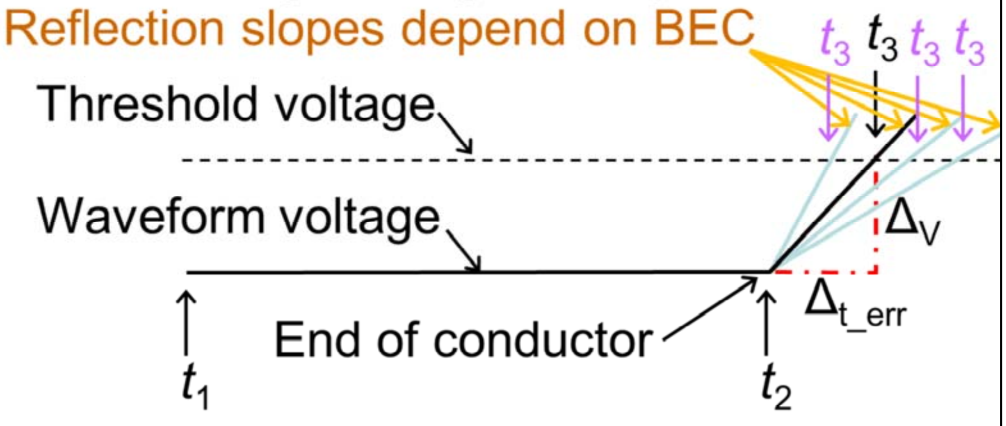
Dry soil, small BEC → Large slope of reflection

Wet soil, BEC ~ 1.7 dS/m → Smaller slope of reflection

While increasing water content would cause an increase in ε and thus a decrease in reflected voltage, the decrease in reflected voltage of the waveform illustrated here for wet Pullman clay loam (green line) is not completely explained by water content increase. The lack of a strong reflection at the end of the probe rods in the wet soil indicates that bulk electrical conductivity (BEC) has increased as the soil wetted. With correct waveform interpretation algorithms, the travel time can still be determined accurately (Schwartz et al., 2013). Most inexpensive and some expensive sensors that claim to be based on TDR do not, however, correctly determine the travel time with consequences in inaccuracy illustrated in the next slide.

Schwartz, R.C., J.J. Casanova, J.M. Bell, and S.R. Evett. 2013. A reevaluation of time domain reflectometry propagation time determination in soils. Vadose Zone J. doi:10.2136/vzj2013.07.0135.

Improper Travel Time Measurement Using Voltage Comparator

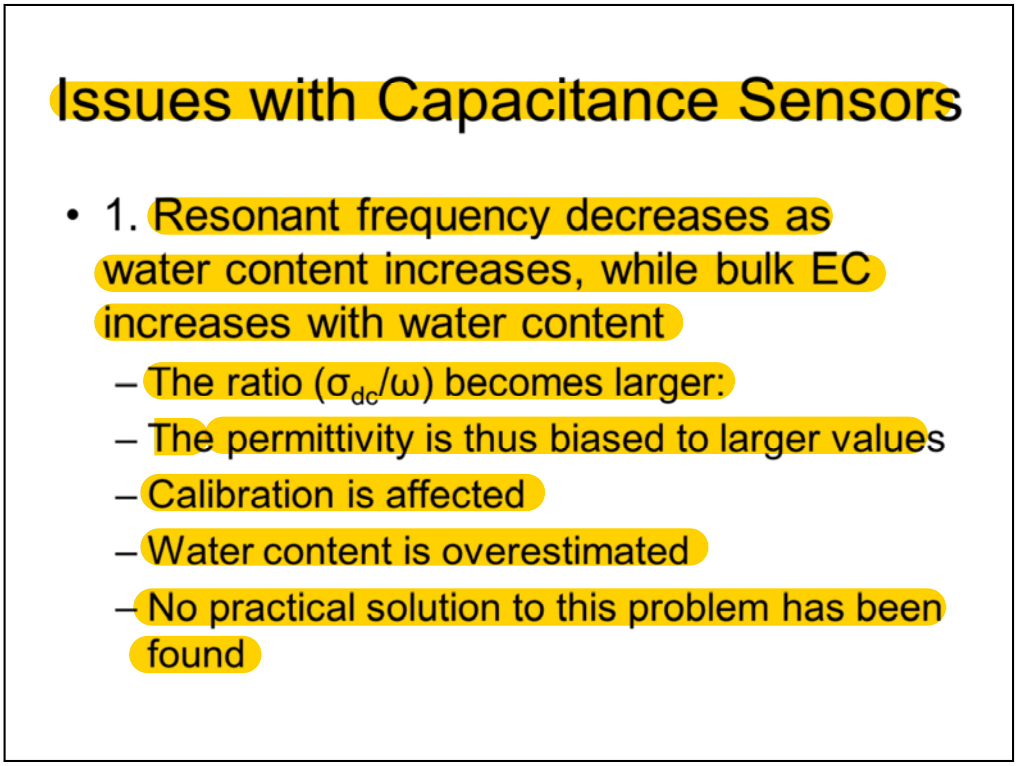


Δ_V/Δ_{t_err} decreases as σ_a increases
Δ_{t_err} increases as σ_a increases; $t_3 \neq t_2$

Inexpensive “TDR” sensors, and some expensive ones, attempt to determine the pulse travel time by comparing the reflected voltage to a threshold voltage using an electronic chip called a voltage comparator. These “TDR” systems do not record the entire waveform and apply waveform interpretation algorithms to determine travel time. They record only the time at which the reflected voltage increases to the value, ΔV, set in the comparator. Because the slope of the pulse reflected at the end of the conductor (waveguide) is influenced by the soil bulk EC, the recorded time includes an error term, Δ_{t_err}, which can change due to the bulk EC, not just the water content. Illustrated here are examples of different slopes of the reflected pulse caused by the different soil bulk EC values.

Examples:

- **Incorrect Travel Time Measurement**
- Trime (IMKO) system
- CS615, CS620, CS616 “water content reflectometers”
- Spectrum TDR300
- **Correct Travel Time Measurement with Waveform Analysis**
- TDR-315, ACC-TDT



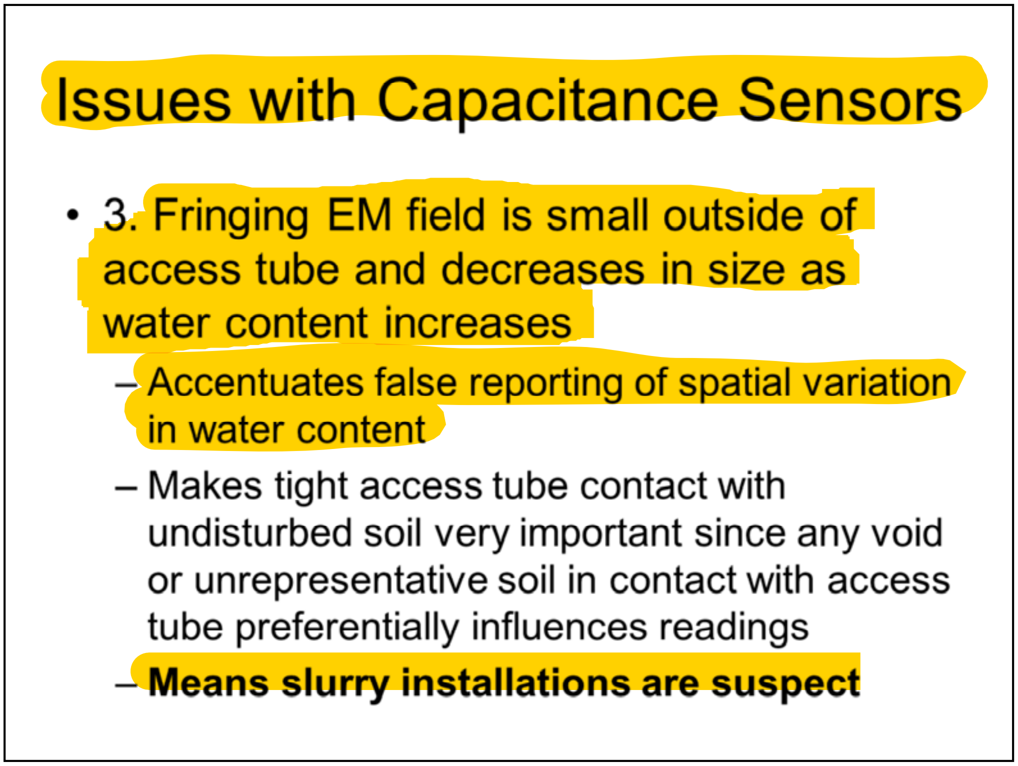
Issues with Capacitance Sensors

- 1. Resonant frequency decreases as water content increases, while bulk EC increases with water content
  - The ratio (σ_{dc}/ω) becomes larger:
  - The permittivity is thus biased to larger values
  - Calibration is affected
  - Water content is overestimated
  - No practical solution to this problem has been found

Bulk electrical conductivity (BEC) of the soil increases with water content and temperature in all soils. The values of BEC and the increases with water content and temperature are larger if the soil contains larger amounts of high activity clays and if the soil contains salts. In fields with widely varying soil textures, the BEC will vary in accordance with the soil texture. This is the basis of soil mapping using VERIS or EM38 technology that responds to BEC. These phenomena apply to vertical changes in soil texture as well. Large differences in soil texture may be found in different soil horizons, and the value of BEC and its relationship with water content and temperature will be different for these different soil horizons. In fields were leaching is used, there will be large vertical changes in BEC due to salt accumulation and flushing.

Issues with Capacitance Sensors

- 2. Electromagnetic field propagation is strongly influenced by small-scale variations in water content and bulk EC associated with soil structure
  - Estimated water content varies randomly
  - Spatial variation across a field is mis-reported
  - Data are not representative of the field or crop water use
  - **Calibration in lab column not useful in field**
  - No solution is expected



Issues with Capacitance Sensors

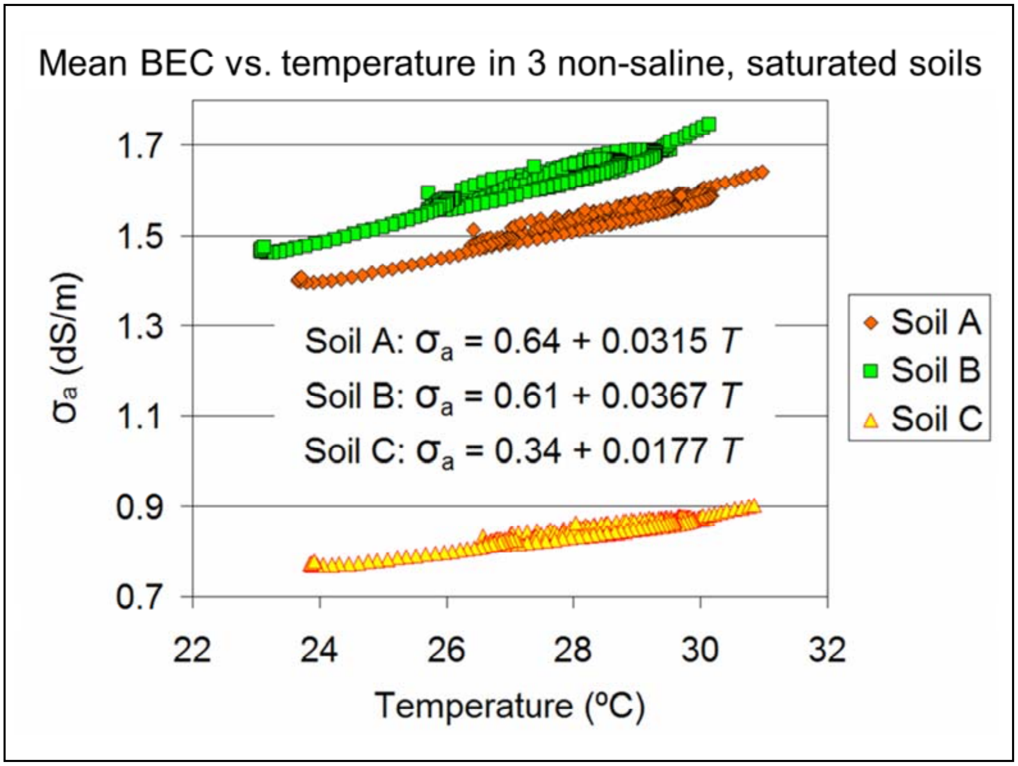
- 3. Fringing EM field is small outside of access tube and decreases in size as water content increases
  - Accentuates false reporting of spatial variation in water content
  - Makes tight access tube contact with undisturbed soil very important since any void or unrepresentative soil in contact with access tube preferentially influences readings
  - **Means slurry installations are suspect**

Issues with Capacitance Sensors

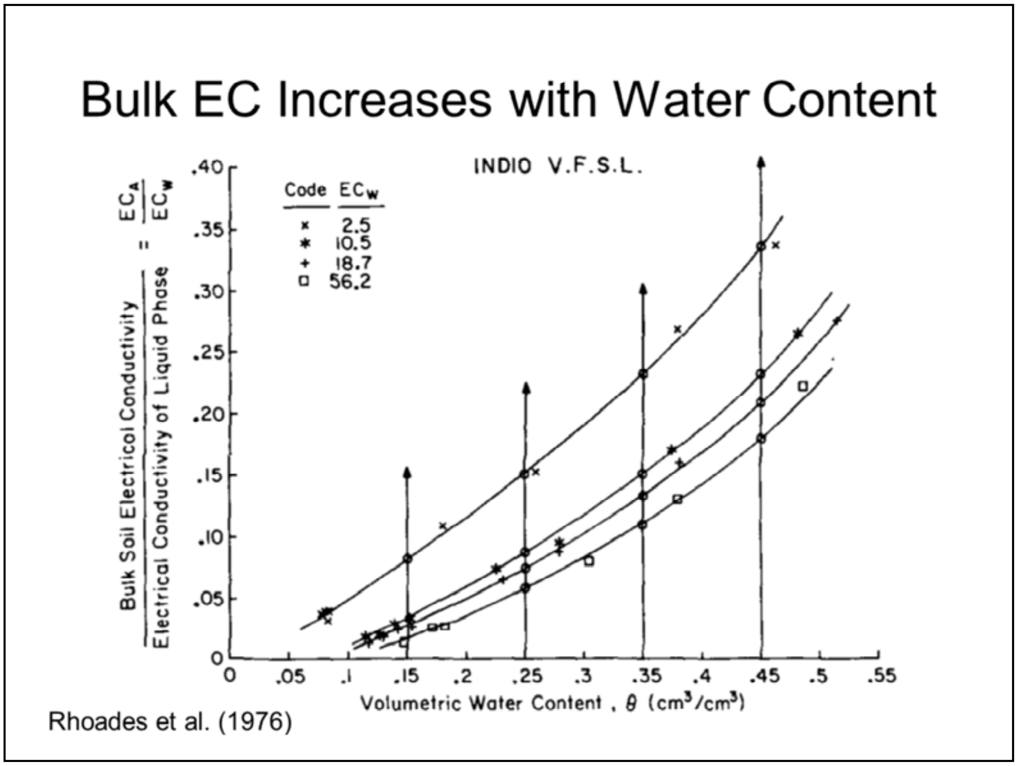
- 4. Calibration is inherently nonlinear
  - Makes calibration difficult because intermediate water contents must be created and accurately measured using volumetric sampling methods
  - Sensitivity to frequency changes is much greater at larger water contents, increasing noise

Importance of Bulk EC

- Bulk EC, σ_a, varies greatly on small and large scales in field soils, vertically & horizontally
- Bulk EC can be large in wet, non-saline soils if they contain active/superactive clays
- Bulk EC affects permittivity more at the smaller frequencies of capacitance sensors
- Bulk EC spatiotemporal variation is strongly affected by irrigation, irrigation application method and soil textural variations
- Bulk EC is strongly dependent on both temperature and water content



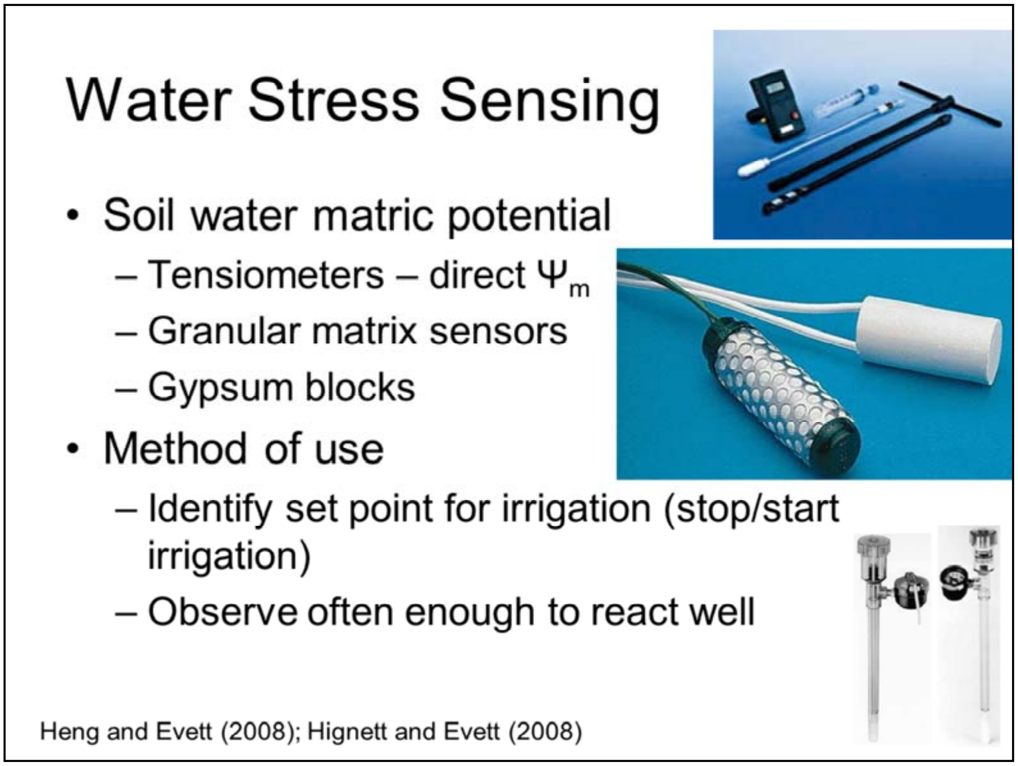
Bulk electrical conductivity was linearly related to temperature, with similar slopes for soils A and B, and with a slope approximately 50% smaller for soil C. The salt content of these soils was negligible, but they contained different amounts off superactive clay.



Bulk EC Increases with Water Content

Rhoades et al. (1976)

Rhoades, J.D., P.A.C. Raats and R.J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J. 40:651-655.



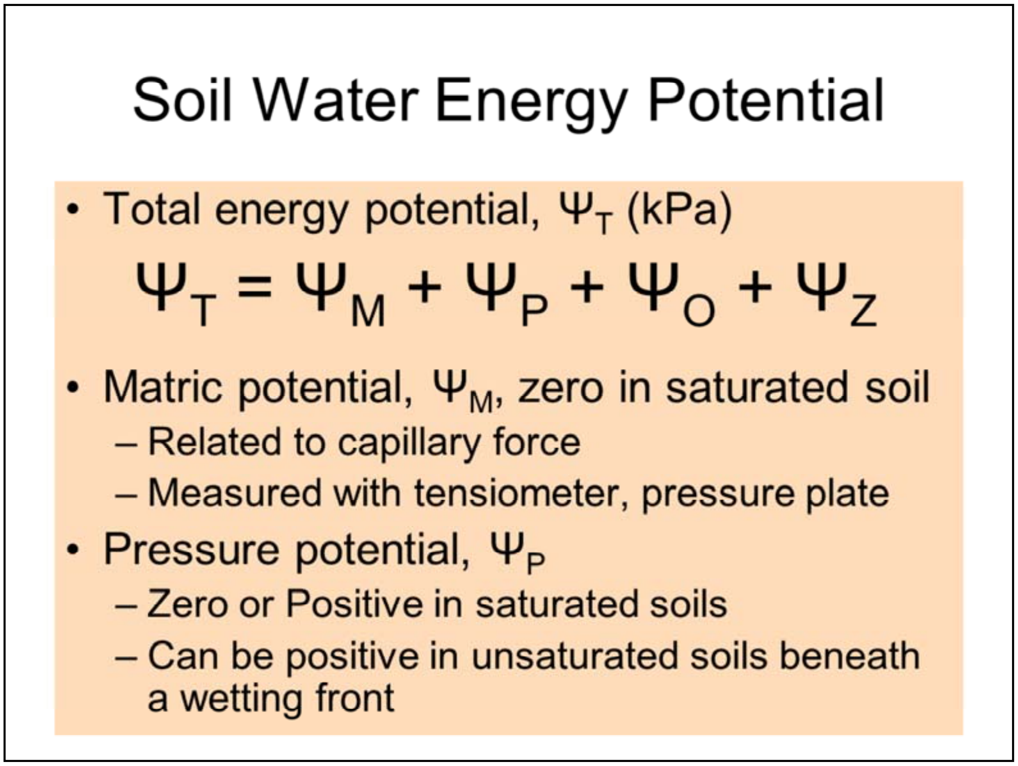
Water Stress Sensing

- Soil water matric potential
  - Tensiometers – direct Ψ_m
  - Granular matrix sensors
  - Gypsum blocks
- Method of use
  - Identify set point for irrigation (stop/start irrigation)
  - Observe often enough to react well

Heng and Evett (2008); Hignett and Evett (2008)

Heng, L.K., and S.R. Evett. Tensiometers. 2008. Chapter 8 (pp. 113-121) *In* S.R. Evett, L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.) Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

Hignett, C., and S.R. Evett. 2008. Electrical Resistance Sensors for Soil Water Tension Estimates. Chapter 9 (pp. 123-129) *In* S.R. Evett, L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.) Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801



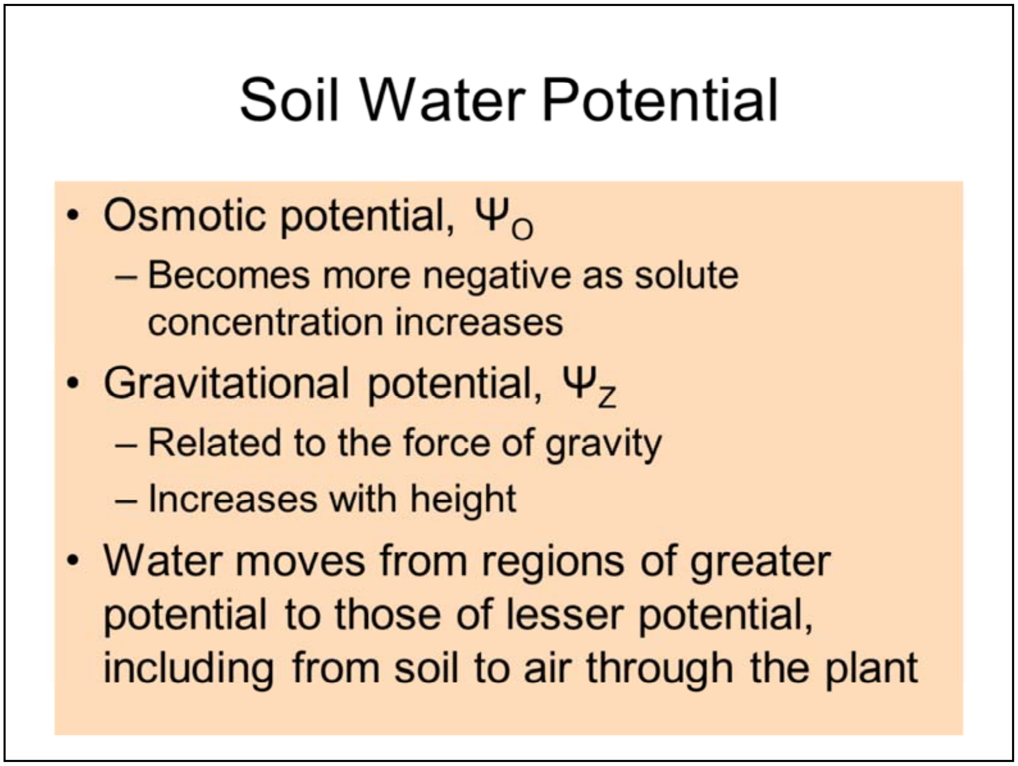
Soil Water Energy Potential

- Total energy potential, Ψ_T (kPa)

$$\Psi_T = \Psi_M + \Psi_P + \Psi_O + \Psi_Z$$

- Matric potential, Ψ_M, zero in saturated soil
  - Related to capillary force
  - Measured with tensiometer, pressure plate
- Pressure potential, Ψ_P
  - Zero or Positive in saturated soils
  - Can be positive in unsaturated soils beneath a wetting front

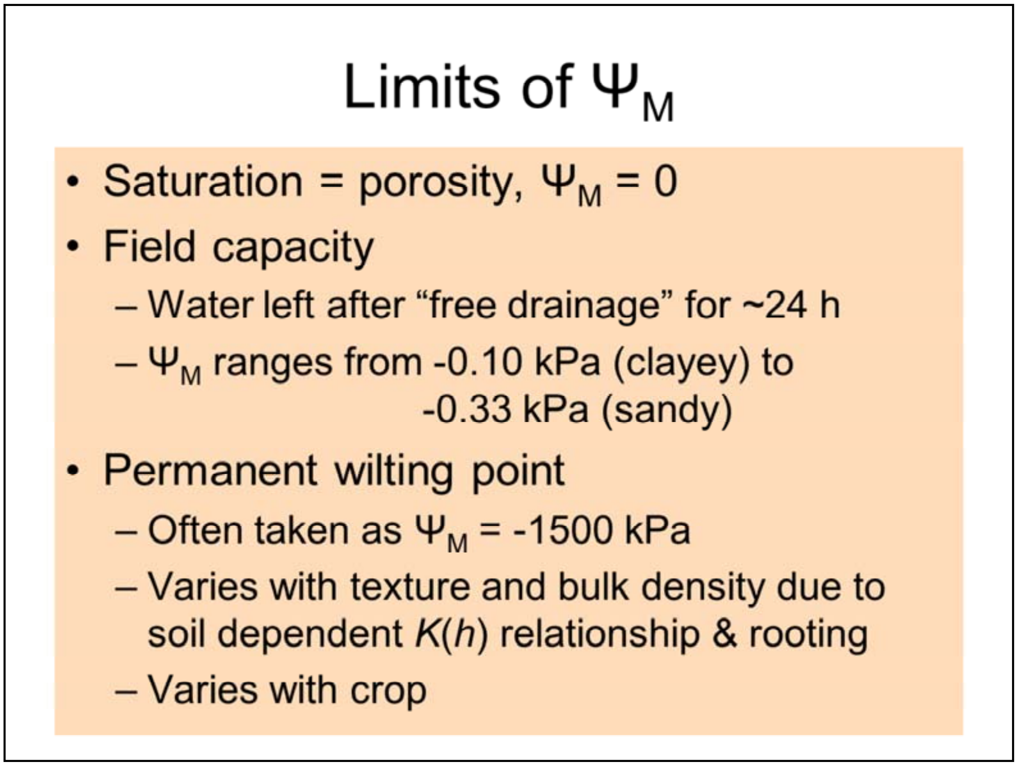
The total energy potential of soil water is affected by four component potentials, the matric potential (Ψ_M) that is related to the capillary force in soil pores and which is zero if the soil is saturated with water, the pressure potential (Ψ_P) that can be zero or positive in saturated soils or beneath a saturated wetting front, the osmotic potential (Ψ_O) that is due to salts in the soil solution, and the gravitational potential (Ψ_Z) that is relative to the reference place, often take as the soil surface. All four components can influence how available soil water is for plant water uptake.



Soil Water Potential

- Osmotic potential, Ψ_O
  - Becomes more negative as solute concentration increases
- Gravitational potential, Ψ_Z
  - Related to the force of gravity
  - Increases with height
- Water moves from regions of greater potential to those of lesser potential, including from soil to air through the plant

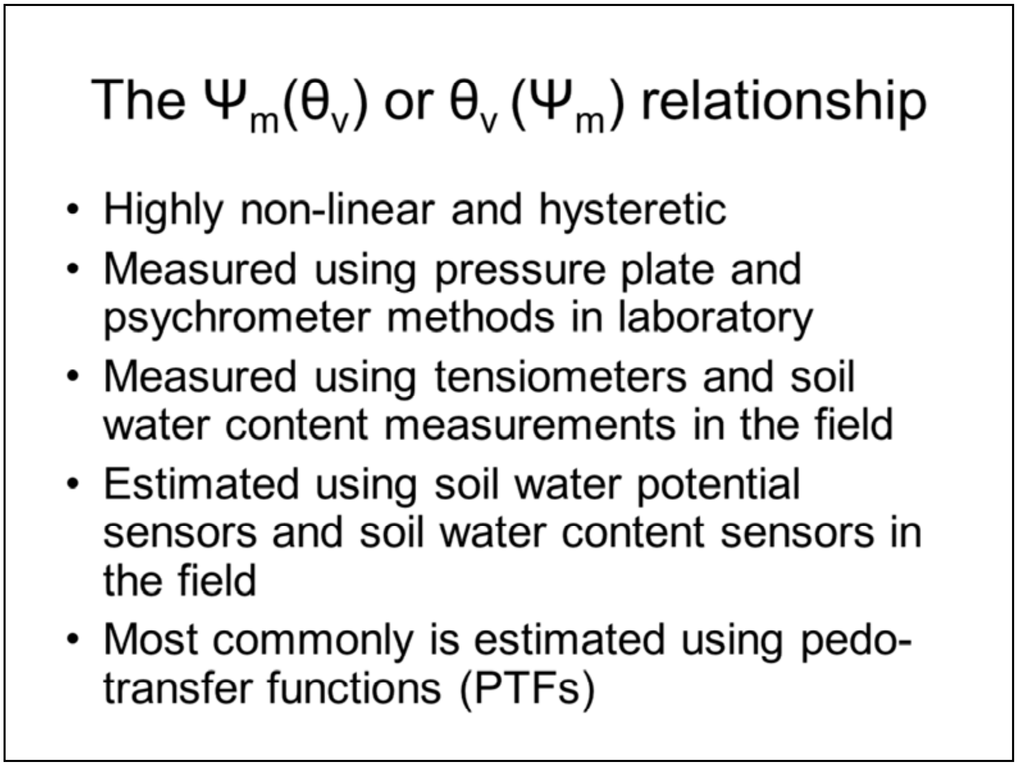
The osmotic potential can influence crop water uptake, and it can damage plants through specific ion effects (e.g., chloride), but is typically small compared with matric potential. The gravitational potential has a small effect on crop water uptake, but is likewise numerically small compared to the matric potential range that occurs with the management allowed depletion range of water content.



Limits of Ψ_M

- Saturation = porosity, $\Psi_M = 0$
- Field capacity
  - Water left after "free drainage" for ~24 h
  - Ψ_M ranges from -0.10 kPa (clayey) to -0.33 kPa (sandy)
- Permanent wilting point
  - Often taken as $\Psi_M = -1500$ kPa
  - Varies with texture and bulk density due to soil dependent *K*(*h*) relationship & rooting
  - Varies with crop

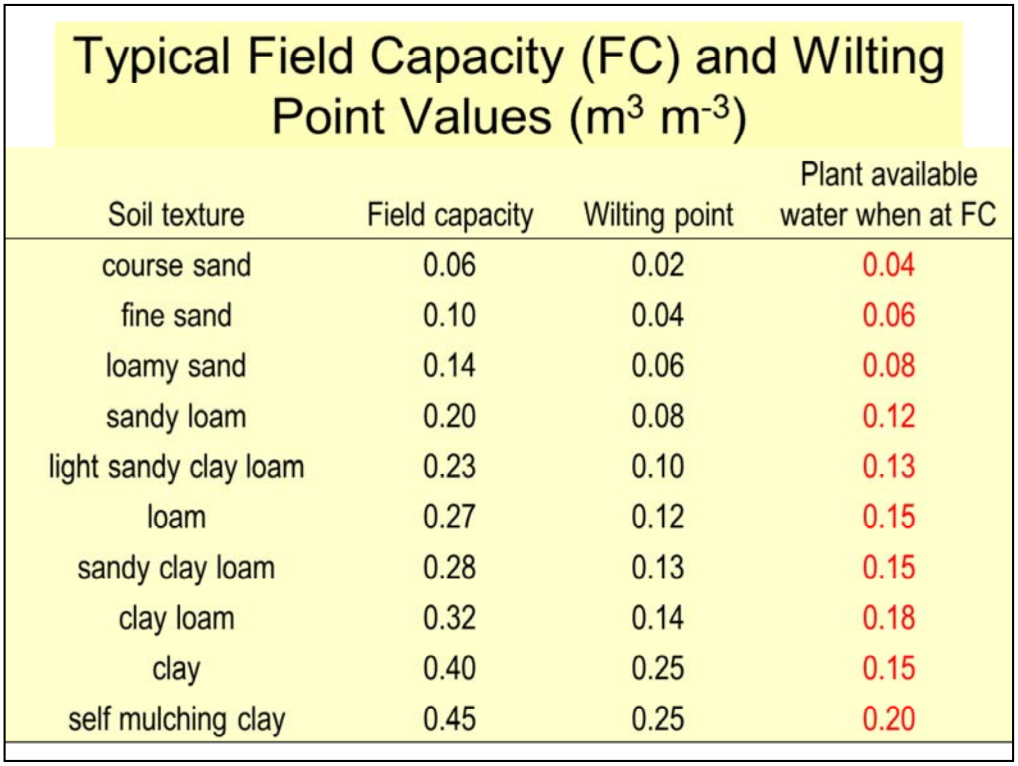
In water management, we typically work with water contents between the so-called field capacity and permanent wilting points. This is by default because water contents greater than field capacity typically change rapidly through redistribution and drainage to deeper soil layers in ways that are not amenable to management, and because water contents that are smaller than that at the wilting point are irrelevant because the crop is permanently damaged if the soil becomes that dry. Crop water management attempts to keep water content in the range of available water holding capacity (AWHC), which is the range from field capacity to permanently wilting point, without approaching the permanent wilting point too closely.



The $\Psi_m(\theta_v)$ or $\theta_v(\Psi_m)$ relationship

- Highly non-linear and hysteretic
- Measured using pressure plate and psychrometer methods in laboratory
- Measured using tensiometers and soil water content measurements in the field
- Estimated using soil water potential sensors and soil water content sensors in the field
- Most commonly is estimated using pedo-transfer functions (PTFs)

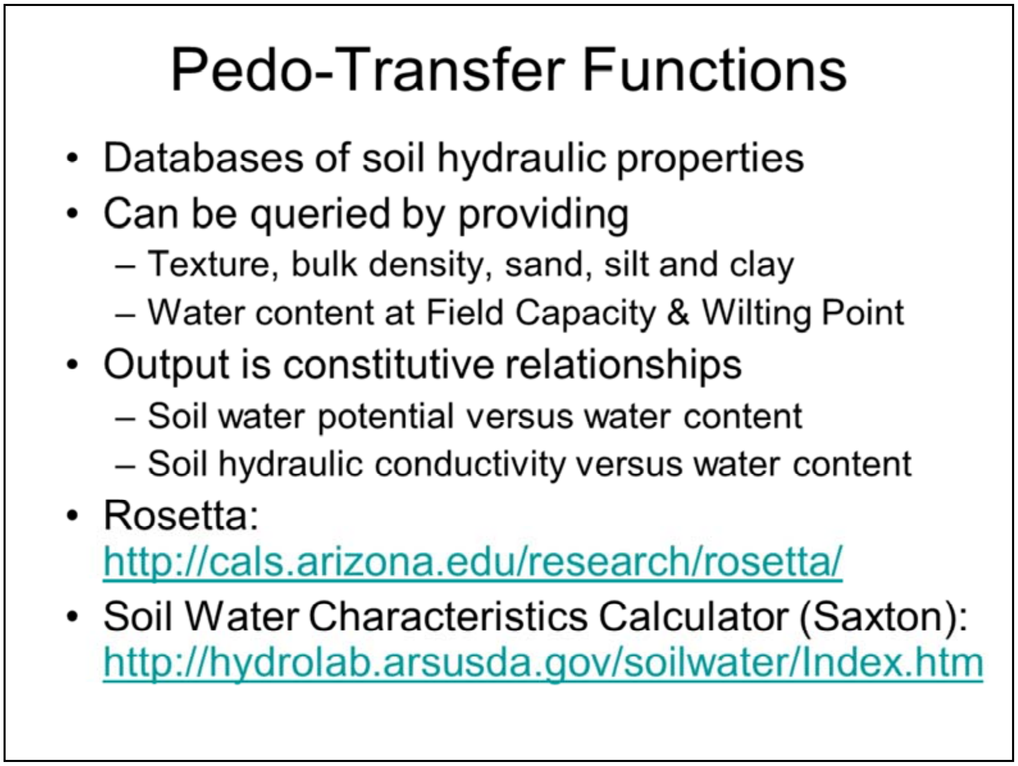
The relationship between soil water content and matric potential is important because it helps us define the field capacity and wilting point water contents for a given soil or soil horizon. The relationship is difficult to determine in the laboratory or field.



Typical Field Capacity (FC) and Wilting Point Values ($m^3\ m^{-3}$)

Soil texture	Field capacity	Wilting point	Plant available water when at FC
course sand	0.06	0.02	0.04
fine sand	0.10	0.04	0.06
loamy sand	0.14	0.06	0.08
sandy loam	0.20	0.08	0.12
light sandy clay loam	0.23	0.10	0.13
loam	0.27	0.12	0.15
sandy clay loam	0.28	0.13	0.15
clay loam	0.32	0.14	0.18
clay	0.40	0.25	0.15
self mulching clay	0.45	0.25	0.20

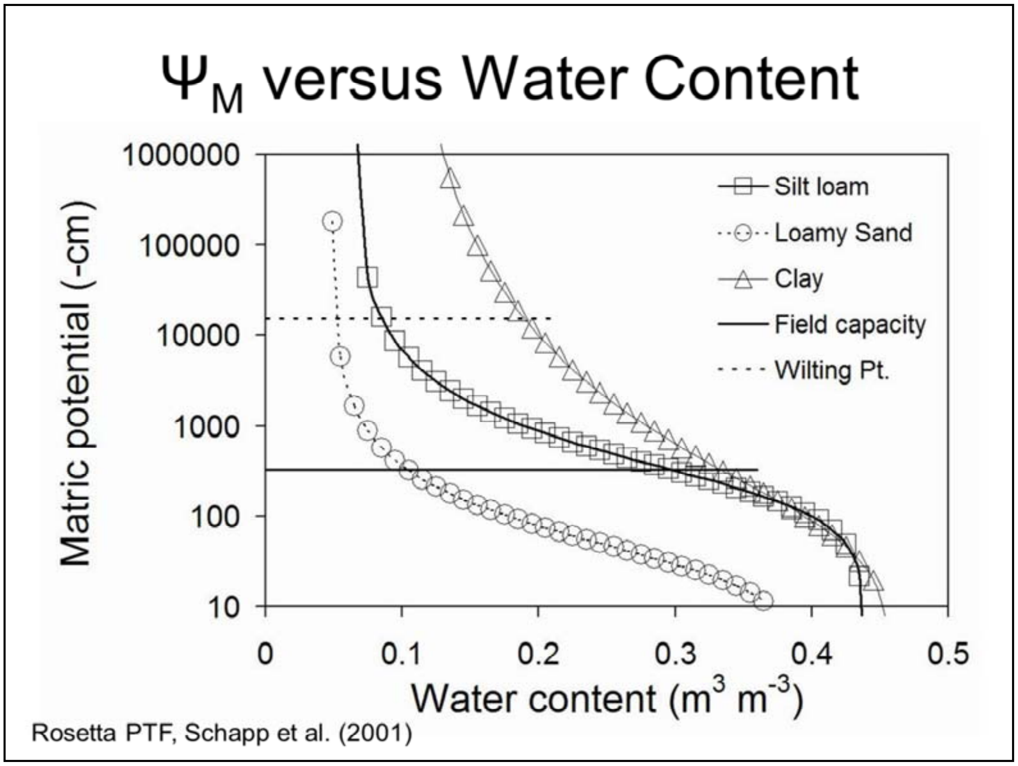
The plant available water holding capacity (AWHC), which is the difference between the water content at field capacity and that at permanent wilting point, varies greatly with soil texture (and bulk density). Since irrigation management effectively takes place within this range of water contents, the accuracy and bias of a sensor system are important to evaluate with reference to the AWHC. Many sensor systems lack the accuracy to be useful for management in medium and coarse textured soils.



Pedo-Transfer Functions

- Databases of soil hydraulic properties
- Can be queried by providing
  - Texture, bulk density, sand, silt and clay
  - Water content at Field Capacity & Wilting Point
- Output is constitutive relationships
  - Soil water potential versus water content
  - Soil hydraulic conductivity versus water content
- Rosetta: http://cals.arizona.edu/research/rosetta/
- Soil Water Characteristics Calculator (Saxton): http://hydrolab.arsusda.gov/soilwater/Index.htm

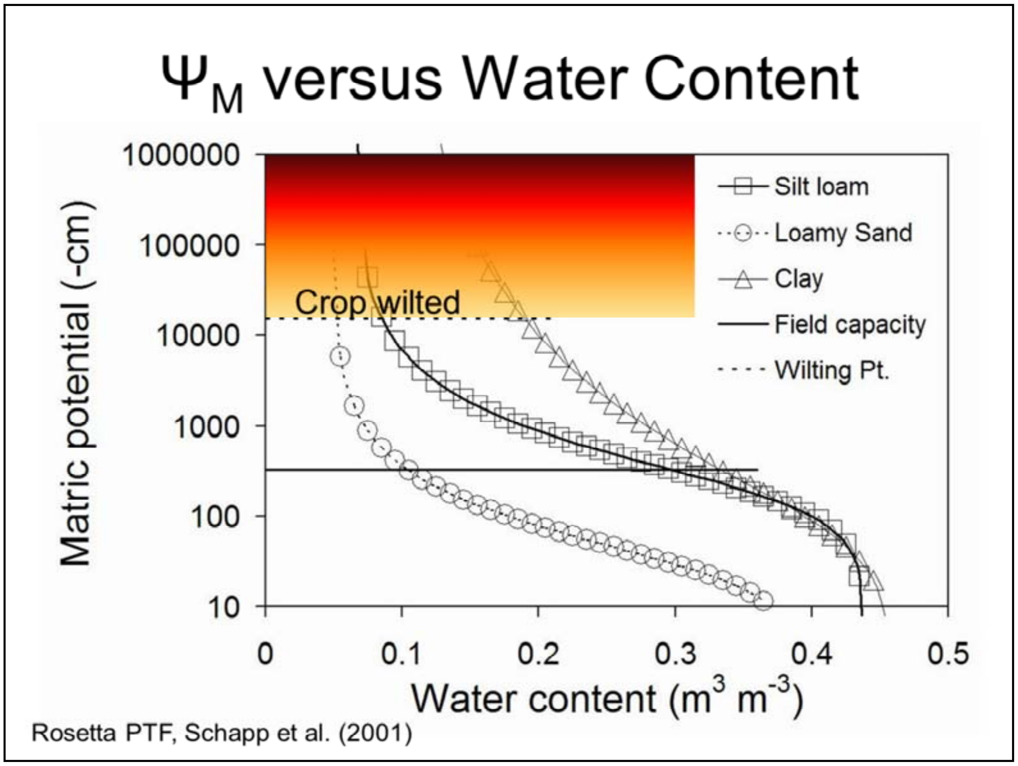
Computerized pedo-transfer functions are available that will provide water content versus matric potential relationships. These should be used with caution due to their approximate nature.



Ψ_M versus Water Content

Rosetta PTF, Schapp et al. (2001)

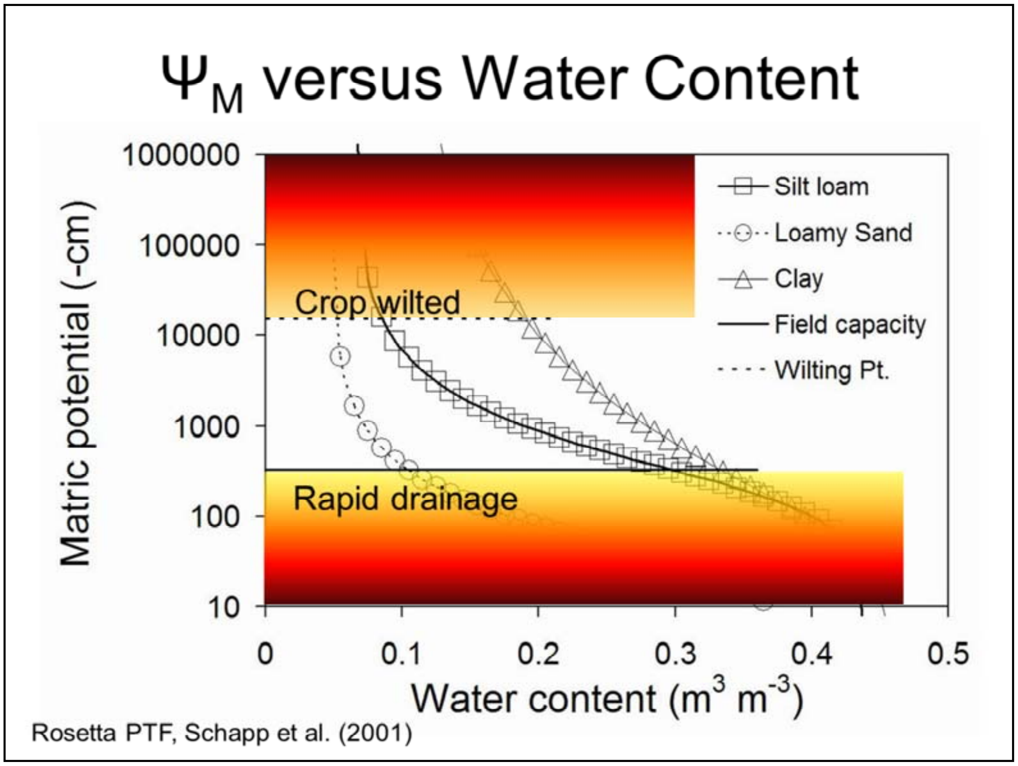
Schaap, M.G., F.J. Leij, and M. Th. van Genuchten, 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology, 251:163-176.



Ψ_M versus Water Content

Rosetta PTF, Schapp et al. (2001)

Schaap, M.G., F.J. Leij, and M. Th. van Genuchten, 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology, 251:163-176.



Ψ_M versus Water Content

Rosetta PTF, Schapp et al. (2001)

Schaap, M.G., F.J. Leij, and M. Th. van Genuchten, 2001. Rosetta: a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Journal of Hydrology, 251:163-176.

Units

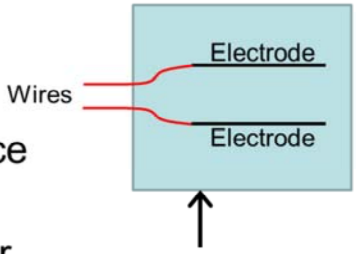
- Length (hydraulic head, *H*, units of meters)
- Energy per unit volume (Ψ, N m^{-2} = Pascal = Pa)

$$\Psi = \rho_w g H$$

- Useful conversions from Warrick (2003) are:
- 105 kPa = 1 bar ≈ 10.22 m of water
  (at g = 9.81 m s^{-2})
- 15 bars ≈ 1500 kPa (typical wilting point value)

Resistance Sensors Respond to Ψ_m

- Granular matrix sensor (GMS)
- Gypsum block
- Use AC resistance/conductance meter
- Resistance decreases as water content of gypsum or granular matrix increases
- Resistance is more directly related to soil matric potential than to volumetric water content



Block of porous gypsum ($CaSO_4$) or body of granular matrix of graded sand sizes with gypsum pellet

Resistance Sensors

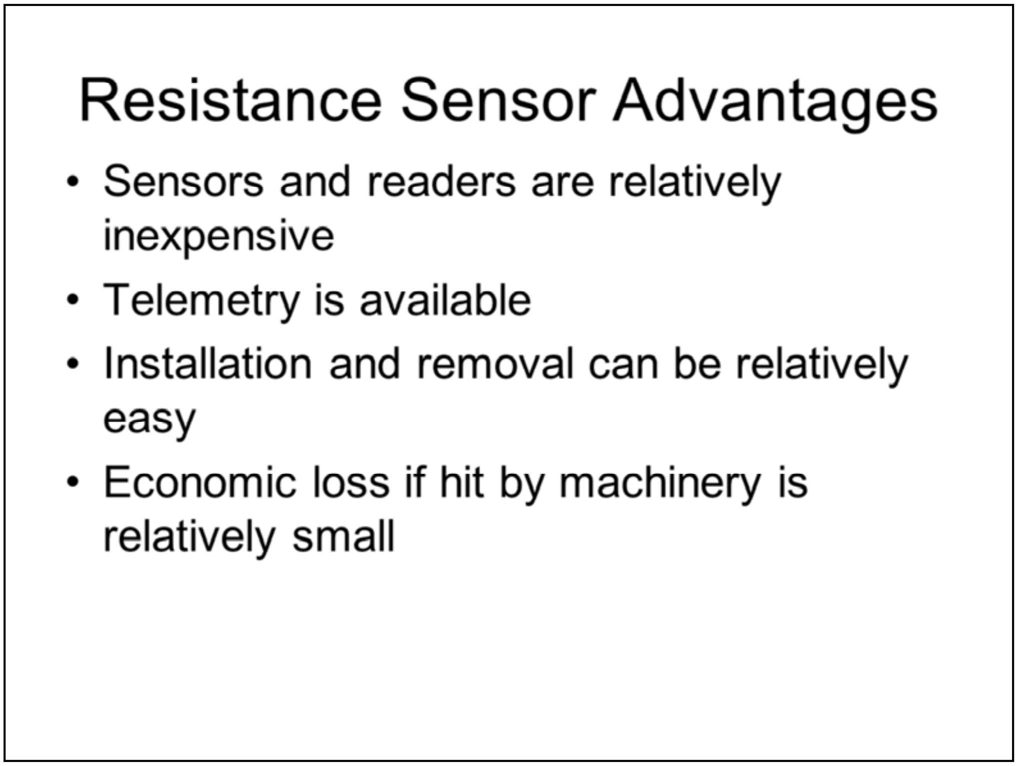
- The gypsum block (or pellet in the GMS) is slightly soluble and buffers the pore water chemistry so that saline soils do not so greatly affect the pore water conductivity within the sensor
- The resistance meter or datalogger must be tuned to alternate the polarity of measurement in order to avoid polarizing the electrodes, which would cause erroneous readings.

Resistance Sensor Issues

- Gypsum will dissolve, changing the porosity of a gypsum block and eventually ruining the sensor
- The gypsum pellet in a GMS will eventually dissolve completely, resulting in biased readings and loss of calibration
- Electrode separation distance and size will influence the reading, so careful manufacturing is important

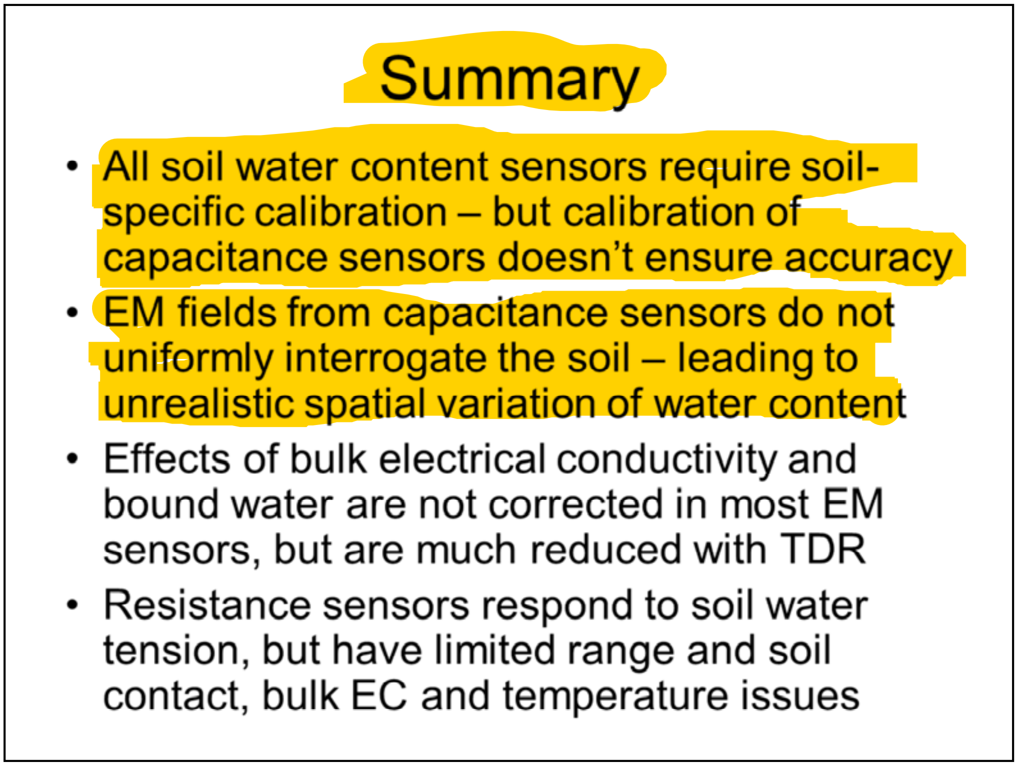
Resistance Sensor Issues

- Sensors are calibrated in terms of soil matric potential, and **conversion of this to soil water content is prone to error**
- Range of readings is limited:
  - -100 to -600 kPa for gypsum blocks
  - -10 to -150 kPa for GMS
- Sensor-soil physical and hydraulic contact can be broken irrecoverably (problematic for deficit irrigation and irrigation broken by fallowing)
- Sensing occurs in the sensor body, not in the soil – equilibrium is assumed!



Resistance Sensor Advantages

- Sensors and readers are relatively inexpensive
- Telemetry is available
- Installation and removal can be relatively easy
- Economic loss if hit by machinery is relatively small



Summary

- All soil water content sensors require soil-specific calibration – but calibration of capacitance sensors doesn't ensure accuracy
- EM fields from capacitance sensors do not uniformly interrogate the soil – leading to unrealistic spatial variation of water content
- Effects of bulk electrical conductivity and bound water are not corrected in most EM sensors, but are much reduced with TDR
- Resistance sensors respond to soil water tension, but have limited range and soil contact, bulk EC and temperature issues

Many of the research results discussed here were the result of an international study commissioned by the International Atomic Energy Agency (IAEA) that sought to compare and evaluate the neutron probe, time domain reflectometry and capacitance methods of soil water content sensing. The IAEA was searching for a method that would replace the neutron probe for the agricultural research efforts that it supports in many countries around the world. Through the IAEA, the research team published a book, Field Estimation of Soil Water Content (Evett et al., 2008), that documented many of its results, including its definitive conclusion that,

> "with the possible exception of tensiometers and the granular matrix resistance sensors, none of the sensors studied is practical for on-farm irrigation scheduling; they are either too inaccurate (capacitance sensors) or too costly and difficult to use (TDR and NMM); (6) for research studies, only the NMM, conventional TDR and direct measurements have acceptable accuracy".

The Acclima sensors were not included in the IAEA study, but later work confirmed that they employ true time domain measurement methods (waveform analysis) and have the accuracy of conventional TDR (Schwartz et al., 2015).

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen. 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. 131 pp. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

Schwartz, R.C., S.R. Evett, S. Anderson and D. Anderson. Evaluation of a direct-coupled TDR for determination of soil water content and bulk electrical conductivity. Submitted to Vadose Zone Journal, 24 August 2015. Accepted 11 Nov 2015. doi: 10.2136/vzj2015.08.0115

Questions

- Steve Evett
  - Research Soil Scientist and Lead Scientist
    Steve.Evett@ars.usda.gov
  - Mobile: 806-584-1018
- Soil and Water Management Research Unit, Conservation & Production Research Laboratory, Bushland, Texas
- Special thanks to Robert Schwartz, Research Soil Scientist
- References follow…

References

Anderson, S.K. 2003. Absolute-reading soil moisture and conductivity sensor. Patent No.: US 6,657,443 B2.

Baumhardt, R.L., R.J. Lascano, and S.R. Evett. 2000. Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. Soil Sci. Soc. Amer. J. 64(6)1940-1946.

Burt, C.M., B. Isbell, and L. Burt. 2003. Long-term salinity buildup on Drip/Micro irrigated trees in California. *In* "Understanding & Addressing Conservation and Recycled Water Irrigation", Proceedings of the International Irrigation Association Technical Conference. Pp. 46-56. November 2003. (CD-ROM)

Cai, G., T. Dang, S. Guo, and M. Hao. 2005. Effect of nutrient and soil management on the efficiency of nitrogen and water use in rainfed wheat in China. p. 196–202. In Nuclear Techniques in Integrated Plant Nutrient, Water and Soil Management: Proc. Int. Symp. Vienna. 16–20 Oct. 2000. C&S Pap. Ser. 11/P. IAEA-TECDOC-1468. Int. Atomic Energy Agency, Vienna.

Evett, S.R. 2003. Measuring soil water by time domain reflectometry. *In* B.A. Stewart and Terry A. Howell (editors). Encyclopedia of Water Science, Marcel Dekker, Inc. New York. Pp. 894-898.

Evett, S.R. 2007. Soil water and monitoring technology. p. 25-84. In R.J. Lascano and R.E. Sojka (ed.) Irrigation of agricultural crops. Agron. Monogr. 30, 2nd ed. ASA, CSSA, and SSSA, Madison, WI. Available at http://www.cprl.ars.usda.gov/wmru/pdfs/C2_Irrigation%20Monograph%2030.pdf

Evett, S.R. 2008. Neutron Moisture Meters. Chapter 3 (pp. 39-54) In S.R. Evett, L.K. Heng, P. Moutonnet and M.L. Nguyen (eds.) Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

Evett, S. R. and Steiner, J. L. 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. Soil Sci. Soc. Am. J. 59(4):961-968.

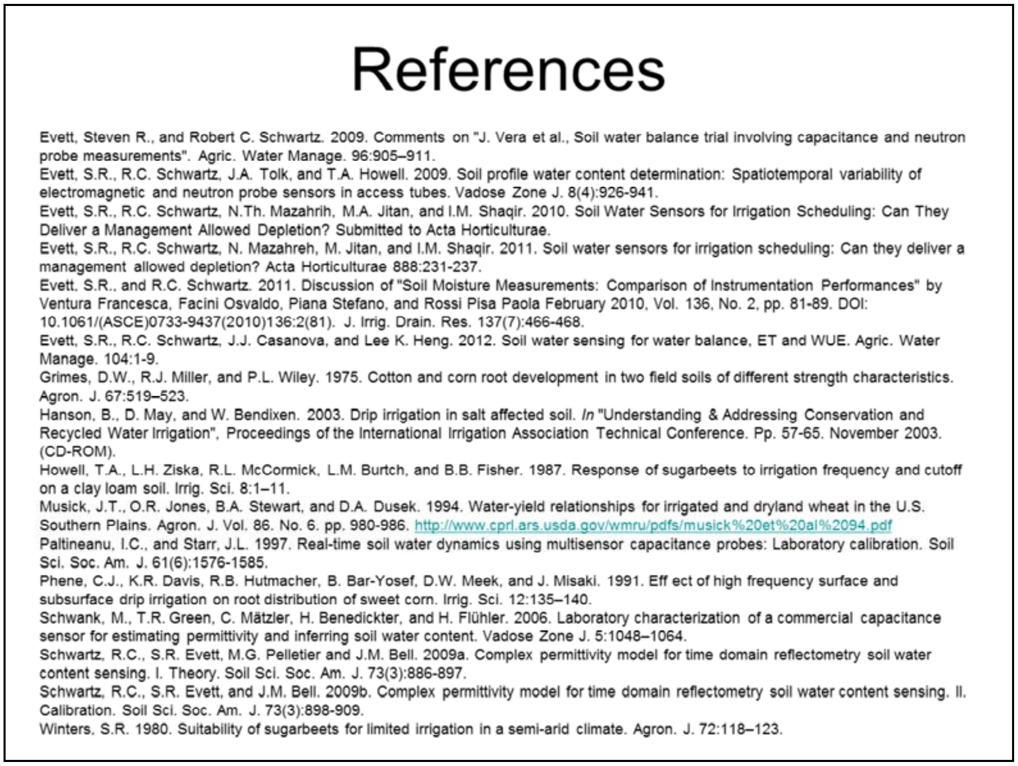
Evett, S.R., B.B. Ruthardt, S.T. Kottkamp, T.A. Howell, A.D. Schneider, and J.A. Tolk. 2002. Accuracy and Precision of Soil Water Measurements by Neutron, Capacitance, and TDR Methods. 17th World Congress of Soil Science, August 14-21, 2002, Bangkok, Thailand, Transactions, pp. 318-1 - 318-8. (CD-ROM). http://www.cprl.ars.usda.gov/wmru/pdfs/wcss0318.pdf

Evett, S.R., J.A. Tolk, and T.A. Howell. 2005. TDR laboratory calibration in travel time, bulk electrical conductivity, and effective frequency. Vadose Zone J. 4:1020–1029.

Evett, S.R., J.A. Tolk, and T.A. Howell. 2006. Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence, and precision. Vadose Zone J. 5:894–907.

Evett, S.R., L.K. Heng, P. Moutonnet and M.L. Nguyen. 2008. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. 131 pp. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018–5518. Available at http://www-pub.iaea.org/mtcd/publications/PubDetails.asp?pubId=7801

More references on next page.



References

Evett, Steven R., and Robert C. Schwartz. 2009. Comments on "J. Vera et al., Soil water balance trial involving capacitance and neutron probe measurements". Agric. Water Manage. 96:905–911.

Evett, S.R., R.C. Schwartz, J.A. Tolk, and T.A. Howell. 2009. Soil profile water content determination: Spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes. Vadose Zone J. 8(4):926-941.

Evett, S.R., R.C. Schwartz, N.Th. Mazahrih, M.A. Jitan, and I.M. Shaqir. 2010. Soil Water Sensors for Irrigation Scheduling: Can They Deliver a Management Allowed Depletion? Submitted to Acta Horticulturae.

Evett, S.R., R.C. Schwartz, N. Mazahreh, M. Jitan, and I.M. Shaqir. 2011. Soil water sensors for irrigation scheduling: Can they deliver a management allowed depletion? Acta Horticulturae 888:231-237.

Evett, S.R., and R.C. Schwartz. 2011. Discussion of "Soil Moisture Measurements: Comparison of Instrumentation Performances" by Ventura Francesca, Facini Osvaldo, Piana Stefano, and Rossi Pisa Paola February 2010, Vol. 136, No. 2, pp. 81-89. DOI: 10.1061/(ASCE)0733-9437(2010)136:2(81). J. Irrig. Drain. Res. 137(7):466-468.

Evett, S.R., R.C. Schwartz, J.J. Casanova, and Lee K. Heng. 2012. Soil water sensing for water balance, ET and WUE. Agric. Water Manage. 104:1-9.

Grimes, D.W., R.J. Miller, and P.L. Wiley. 1975. Cotton and corn root development in two field soils of different strength characteristics. Agron. J. 67:519–523.

Hanson, B., D. May, and W. Bendixen. 2003. Drip irrigation in salt affected soil. *In* "Understanding & Addressing Conservation and Recycled Water Irrigation", Proceedings of the International Irrigation Association Technical Conference. Pp. 57-65. November 2003. (CD-ROM).

Howell, T.A., L.H. Ziska, R.L. McCormick, L.M. Burtch, and B.B. Fisher. 1987. Response of sugarbeets to irrigation frequency and cutoff on a clay loam soil. Irrig. Sci. 8:1–11.

Musick, J.T., O.R. Jones, B.A. Stewart, and D.A. Dusek. 1994. Water-yield relationships for irrigated and dryland wheat in the U.S. Southern Plains. Agron. J. Vol. 86. No. 6. pp. 980-986. http://www.cprl.ars.usda.gov/wmru/pdfs/musick%20et%20al%2094.pdf

Paltineanu, I.C., and Starr, J.L. 1997. Real-time soil water dynamics using multisensor capacitance probes: Laboratory calibration. Soil Sci. Soc. Am. J. 61(6):1576-1585.

Phene, C.J., K.R. Davis, R.B. Hutmacher, B. Bar-Yosef, D.W. Meek, and J. Misaki. 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. Irrig. Sci. 12:135–140.

Schwank, M., T.R. Green, C. Mätzler, H. Benedickter, and H. Flühler. 2006. Laboratory characterization of a commercial capacitance sensor for estimating permittivity and inferring soil water content. Vadose Zone J. 5:1048–1064.

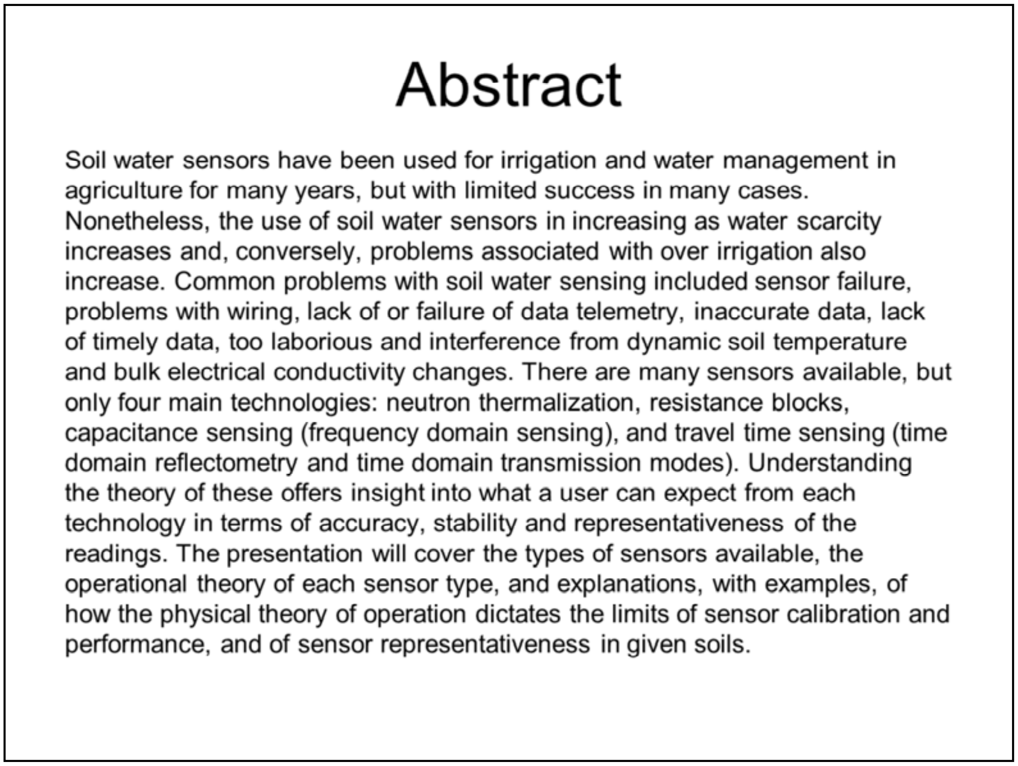
Schwartz, R.C., S.R. Evett, M.G. Pelletier and J.M. Bell. 2009a. Complex permittivity model for time domain reflectometry soil water content sensing. I. Theory. Soil Sci. Soc. Am. J. 73(3):886-897.

Schwartz, R.C., S.R. Evett, and J.M. Bell. 2009b. Complex permittivity model for time domain reflectometry soil water content sensing. II. Calibration. Soil Sci. Soc. Am. J. 73(3):898-909.

Winters, S.R. 1980. Suitability of sugarbeets for limited irrigation in a semi-arid climate. Agron. J. 72:118–123.

Acknowledgments & Disclosures

- This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas AgriLife Research, Texas AgriLife Extension Service, Texas Tech University, and West Texas A&M University



Abstract

Soil water sensors have been used for irrigation and water management in agriculture for many years, but with limited success in many cases. Nonetheless, the use of soil water sensors in increasing as water scarcity increases and, conversely, problems associated with over irrigation also increase. Common problems with soil water sensing included sensor failure, problems with wiring, lack of or failure of data telemetry, inaccurate data, lack of timely data, too laborious and interference from dynamic soil temperature and bulk electrical conductivity changes. There are many sensors available, but only four main technologies: neutron thermalization, resistance blocks, capacitance sensing (frequency domain sensing), and travel time sensing (time domain reflectometry and time domain transmission modes). Understanding the theory of these offers insight into what a user can expect from each technology in terms of accuracy, stability and representativeness of the readings. The presentation will cover the types of sensors available, the operational theory of each sensor type, and explanations, with examples, of how the physical theory of operation dictates the limits of sensor calibration and performance, and of sensor representativeness in given soils.

Abstract - Soil water sensors have been used for irrigation and water management in agriculture for many years, but with limited success in many cases. Nonetheless, the use of soil water sensors in increasing as water scarcity increases and, conversely, problems associated with over irrigation also increase. Common problems with soil water sensing included sensor failure, problems with wiring, lack of or failure of data telemetry, inaccurate data, lack of timely data, too laborious and interference from dynamic soil temperature and bulk electrical conductivity changes. There are many sensors available, but only four main technologies: neutron thermalization, resistance blocks, capacitance sensing (frequency domain sensing), and travel time sensing (time domain reflectometry and time domain transmission modes). Understanding the theory of these offers insight into what a user can expect from each technology in terms of accuracy, stability and representativeness of the readings. The presentation will cover the types of sensors available, the operational theory of each sensor type, and explanations, with examples, of how the physical theory of operation dictates the limits of sensor calibration and performance, and of sensor representativeness in given soils.