

5TE

*Water Content, EC
and Temperature Sensor*



Decagon Devices, Inc.

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1 Introduction

Thank you for choosing Decagon's 5TE Water Content, Temperature, and Electrical Conductivity (EC) sensor. This manual can help you understand the sensor features and ensure successful sensor operation. We hope you find the contents of this manual useful in understanding your instrument and maximizing its benefit to you.

There are several ways to contact Decagon if you ever need assistance with your product, have any questions, or feedback. Decagon has Customer Service Representatives available to speak with you Monday through Friday, between 7am and 5pm Pacific time.

Note: If you purchased your sensor through a distributor, please contact them for assistance.

Email:

support@decagon.com or **sales@decagon.com**

Phone:

509-332-5600

Fax:

509-332-5158

If contacting us by email or fax, please include as part of your message your instrument serial number, your name, address, phone, fax number, and a description of your problem or question.

Please read these instructions before operating your sensor to ensure that it performs to its full potential.

1.1 Warranty

The sensor has a 30-day satisfaction guarantee and a one-year warranty on parts and labor. Your warranty automatically validates upon receipt of the instrument.

1.2 Seller's Liability

Seller warrants new equipment of its own manufacture against defective workmanship and materials for a period of one year from the date of receipt of equipment.

Note: We do not consider the results of ordinary wear and tear, neglect, misuse, accident as defects.

The Seller's liability for defective parts shall in no event exceed the furnishing of replacement parts "freight on board" the factory where originally manufactured. Material and equipment covered hereby which is not manufactured by Seller shall be covered only by the warranty of its manufacturer. Seller shall not be liable to Buyer for loss, damage or injuries to persons (including death), or to property or things of whatsoever kind (including, but not without limitation, loss of anticipated profits), occasioned by or arising out of the installation, operation, use, misuse, nonuse, repair, or replacement of said material and equipment, or out of the use of any method or process for which the same may be employed. The use of this equipment constitutes Buyer's acceptance of the terms set forth in this warranty. There are no understandings, representations, or warranties of any kind, express, implied, statutory or otherwise (including, but without limitation, the implied warranties of merchantability and fitness for a particular purpose), not expressly set forth herein.

2 About 5TE

We designed the 5TE to measure the water content, electrical conductivity, and temperature of soil. The 5TE uses an oscillator running at 70 MHz to measure the dielectric permittivity of soil to determine the water content. A thermistor in thermal contact with the sensor prongs provides the soil temperature, while the screws on the surface of the sensor form a two-sensor electrical array to measure electrical conductivity. The Polyurethane coating on the 5TE circuit board protects the components from water damage and gives the sensor a longer life span.

2.1 Specifications

Volumetric Water Content

Range: Apparent dielectric permittivity (ε_a): 1 (air) to 80 (water)

Resolution: ε_a : $0.1 \varepsilon_a$ (unitless) from 1 to 20, $< 0.75 \varepsilon_a$ (unitless) from 20 to 80 VWC: $0.0008 \text{ m}^3/\text{m}^3$ (0.08% VWC) from 0 to 50% VWC

Accuracy: ε_a : $\pm 1 \varepsilon_a$ (unitless) from 1 to 40 (soil range), $\pm 15\%$ from 40 to 80 (VWC)

- Using Topp equation: $\pm 0.03 \text{ m}^3/\text{m}^3$ ($\pm 3\%$ VWC) typical in mineral soils that have solution electrical conductivity $< 10 \text{ dS/m}$
- Using medium specific calibration, ± 0.01 to $0.02 \text{ m}^3/\text{m}^3$ (± 1 to 2% VWC) in any porous medium.

Electrical Conductivity (bulk)

Range: 0 to 23 dS/m (bulk)

Resolution: 0.01 dS/m from 0 to 7 dS/m , 0.05 dS/m from 7 to 23 dS/m

Accuracy: $\pm 10\%$ from 0 to 7 dS/m , user calibration required above 7 dS/m .

Temperature

Range: -40 to 60 °C

Resolution: 0.1 °C

Accuracy: ± 1 °C

General

Dimensions: 10 cm (l) x 3.2 cm (w) x 0.7 cm (d)

Prong Length: 5.2 cm

Dielectric Measurement Frequency: 70 MHz

Measurement Time: 150 ms (milliseconds)

Power requirements: 3.6 to 15 VDC, 0.3 mA quiescent, 10 mA during 150 ms measurement

Output: RS232 (TTL) or SDI-12

Operating Temperature:¹ -40 to 60 °C

Connector Types: 3.5 mm (stereo) plug or stripped & tinned lead wires (Pigtail)

Cable Length: 5 m standard; custom cable length available upon request

Data logger Compatibility (not exclusive):

- Decagon: Em50, Em50R, and Em50G
- Campbell Scientific: Any logger with serial I/O (CR10X, CR850, 1000, 3000, etc.)

¹Customers may use sensors at higher temperatures under some conditions, please contact Decagon for assistance.

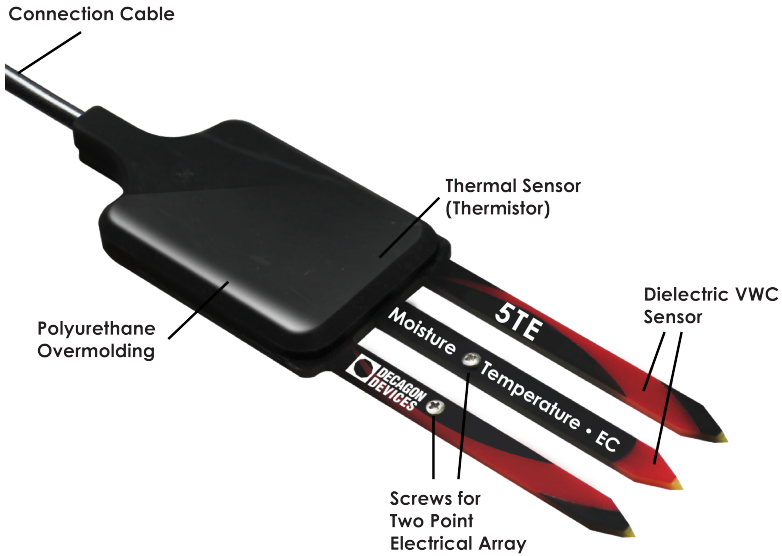


Figure 1: 5TE Components

2.2 Background

In 2006, Decagon incorporated research from its EC-5 volumetric water content sensor into the ECH2O-TE, a sensor that measures volumetric water content, temperature, and electrical conductivity. The new 5TE uses the same theory as the ECH2O-TE, but the 5TE uses stainless steel screws instead of gold traces for the EC measurement. The stainless steel screws make the 5TE a more robust sensor. Additionally, the 5TE utilizes a five point dielectric calibration to provide more accurate dielectric permittivity measurements than the previous ECH2O-TE. In 2014, we changed the overmolding on the sensor circuitry from macromelt to polyurethane to extend the life of the sensor.

3 Theory

3.1 Volumetric Water Content

The 5TE sensor uses an electromagnetic field to measure the dielectric permittivity of the surrounding medium. The sensor supplies a 70 MHz oscillating wave to the sensor prongs that charges according to the dielectric of the material. The stored charge is proportional to soil dielectric and soil volumetric water content. The 5TE microprocessor measures the charge and outputs a value of dielectric permittivity from the sensor.

3.2 Temperature

The 5TE uses a surface-mounted thermistor to take temperature readings. The thermistor is underneath the sensor overmold, next to one of the prongs, and it reads the temperature of the prong surface. The 5TE outputs temperature in °C unless otherwise stated in DataTrac 3 or ECH2O Utility preferences file.

It is important to note that if the black polyurethane overmold of the sensor is in direct sunshine, the temperature measurement may read high. We do not recommend that the sensor be installed with the overmold in the sun.

3.3 Electrical Conductivity

Electrical conductivity (EC) is the ability of a substance to conduct electricity and can be used to infer the amount of polar molecules that are in solution. Measure EC by applying an alternating electrical current to two electrodes and measuring the resistance between them. Conductivity is then derived by multiplying the inverse of the resistance (conductance) by the cell constant (the ratio of the distance between the electrodes to their area).

The 5TE uses a two-sensor array to measure the EC. 5TE The array

is located on the screws of two of the 5TE prongs. 5TE EC measurements are normalized to 25 °C See the sensor cleaning section at the end of this manual for instructions on cleaning the sensors if contamination occurs.

Note: Small amounts of oil from skin contact with the screws will cause significant inaccuracy in the EC measurement.

The 5TE uses a two electrode array to measure the bulk EC of the surrounding medium. Decagon factory calibrates the bulk EC measurement to be accurate within $\pm 10\%$ from 0 to 7 dS/m. This range is adequate for most field, greenhouse and nursery applications. However, some special applications in salt affected soils may require measurements with bulk EC greater than the specified range. The 5TE can measure up to 23.1 dS/m bulk EC, but requires user calibration above 7 dS/m. Additionally, EC measurements above 7 dS/m are sensitive to contamination of the electrodes by skin oils, etc. Be sure to read the sensor cleaning section at the end of the manual if you plan to measure the EC of salty soils.

3.4 Converting Bulk EC to Pore EC

For many applications, it is advantageous to know the electrical conductivity of the solution contained in the soil pores (σ_p), which is a good indicator of the solute concentration in the soil. Researchers have traditionally obtained σ_p by extracting pore water from the soil and measuring σ_p directly. However, this is a time consuming and labor intensive process.

The 5TE measures the electrical conductivity of the bulk soil surrounding the sensors (σ_b). We have conducted a considerable amount of research to determine the relationship between σ_b and σ_p . Recent work by Hilhorst (2000) takes advantage of the linear relationship between the soil bulk dielectric permittivity (ε_b) and σ_b to allow accurate conversion from σ_b to σ_p if you know the ε_b . The 5TE measures ε_b and σ_b nearly simultaneously in the same soil volume, so it is well suited to this method.

Use Hilhorst, 2000 to derive the pore water conductivity.

$$\sigma_p = \frac{\varepsilon_p \sigma_b}{\varepsilon_b - \varepsilon_{\sigma b=0}}$$

where σ_p is the pore water electrical conductivity (dS/m); ε_p is the real portion of the dielectric permittivity of the soil pore water (unitless); σ_b is the bulk electrical conductivity, (dS/m), measured directly by the 5TE; ε_b is the real portion of the dielectric permittivity of the bulk soil (unitless); $\varepsilon_{\sigma b=0}$ is the real portion of the dielectric permittivity of the soil when bulk electrical conductivity is 0 (unitless).

ε_p can be calculated from soil temperature using a simple formula.

$$\varepsilon_p = 80.3 - 0.37 * (T_{soil} - 20)$$

The 5TE measures T_{soil} or soil temperature ($^{\circ}\text{C}$) and ε_b . You can convert raw VWC counts to bulk dielectric with the 5TE dielectric calibration.

$$\varepsilon_b = \frac{\varepsilon_{Raw}}{50}$$

Finally, $\varepsilon_{\sigma b=0}$ is an offset term loosely representing the dielectric of the dry soil. Hilhorst (2000) recommends using $\varepsilon_{\sigma b=0} = 4.1$ as a generic offset. However, our research in several agricultural soils, organic, and inorganic growth media indicates that $\varepsilon_{\sigma b=0} = 6$ results in more accurate determinations of σ_p . Hilhorst (2000) offers a simple and easy method for determining for individual soil types, which will improve the accuracy of the calculation of σ_p in most cases.

Our testing indicates that the above method for calculating σ_p results in good accuracy ($\pm 20\%$) in moist soils and other growth media. In dry soils where VWC is less than about $0.10 \text{ m}^3/\text{m}^3$, the denominator of pore water conductivity equation becomes very small, leading to large potential errors. We recommend you not use this method to calculate σ_p in soils with $\text{VWC} < 0.10 \text{ m}^3/\text{m}^3$.

3.5 Pore Water Versus Solution EC

As noted in the section on “Converting Bulk EC to Pore EC,” you can calculate pore water electrical conductivity from bulk EC using

the sensor-measured dielectric permittivity of the medium. However, pore water EC is not the same as solution EC. Pore water EC is the electrical conductivity of the water in the pore space of the soil. One could measure this directly by squeezing the soil under high pressure to force water out of the soil matrix and test the collected water for EC.

Solution EC is the electrical conductivity of pore water removed from a saturated paste. In this case, wet the soil with distilled water until the soil saturates, then place the soil on filter paper in a vacuum funnel and apply suction. An electrical conductivity measurement on the removed sample water gives the solution electrical conductivity. Theoretically, the two are related by the bulk density. An example calculation illustrates this relationship. If a soil is at 0.1 m³/m³ VWC, has a pore water EC of 0.7 dS/m, and a bulk density of 1.5 Mg/m³. We can calculate the solution EC with two equations.

$$\phi = 1 - \frac{\rho_b}{\rho_s} = 1 - \frac{1.5}{2.65} = 0.43$$

$$\text{Solution EC} = \frac{\sigma_p \theta + \sigma_d(\phi - \theta)}{\phi} = \frac{0.7(0.1) + 0}{0.43} = 0.162 \text{ dS/m}$$

In this example, ϕ is the porosity, ρ_b is bulk density, ρ_s is the density of the minerals (assumed to be 2.65 Mg/m³), the subscript d is distilled water, and θ is volumetric water content. We assume that the EC of the distilled water is 0 dS/m. In practice, solution EC calculated from this method and solution EC taken from a laboratory soil test may not correlate because wetting soil to a saturated paste is very imprecise.

Reference

Hilhorst, M.A. 2000. A pore water conductivity sensor. *Soil Science Society of America Journal* 64:6 1922-1925.

4 Calibration

4.1 Dielectric Permittivity

Decagon factory calibrates each 5TE sensor to measure dielectric permittivity (ε_a) accurately in the range of 1 (air) to 80 (water). The unprocessed raw values reported by the 5TE in standard serial communication have units of $\varepsilon_a * 50$. When used in SDI- 12 communication mode, the unprocessed values have units of ε_a (for 5TE board versions R2-04 and older, units are, $\varepsilon_a * 100$).

4.2 Mineral Soil Calibration

Numerous researchers have studied the relationship between dielectric permittivity and volumetric water content (VWC) in soil. As a result, numerous transfer equations that predict VWC from measured dielectric permittivity. You are free to use any of these various transfer equations to convert raw dielectric permittivity data from the 5TE into VWC. If you choose the mineral soil calibration option in Decagon's ProCheck reader, DataTrac3, or ECH2O Utility, they convert raw dielectric permittivity values with the Topp equation (Topp et al. 1980).

$$\text{VWC} = 4.3 * 10^{-6} \varepsilon_a^3 - 5.5 * 10^{-4} \varepsilon_a^2 + 2.92 * 10^{-2} \varepsilon_a - 5.3 * 10^{-2}$$

Our tests show that in a properly installed 5TE sensor in a normal mineral soil with saturation extract electrical conductivity < 10 dS/m, the Topp equation results in measurements within $\pm 3\%$ VWC of the actual soil VWC. If you require more accurate VWC than $\pm 3\%$, are working in a soil with very high electrical conductivity, or non-normal mineralogy, then it may be necessary to conduct a soil specific calibration for your 5TE sensor to improve the accuracy to 1 to 2% for any soil. For more information on how to perform your own soil-specific calibration, or to have Decagon's calibration service perform one for you, visit us online at <http://www.decagon.com/services/soil-moisture-sensor-custom-calibration>.

Reference

Topp, G.C., J.L. David, and A.P. Annan 1980. Electromagnetic, Determination of Soil Water Content: Measurement in Coaxial Transmission Lines. *Water Resources Research* 16:3. p. 574-582.

5 Connecting Sensors

Decagon designed the 5TE sensor for use with our Em50 series data loggers or the ProCheck handheld reader. The standard sensor (with a 3.5 mm “stereo plug” connector) quickly connects to and is easily configured within a Decagon logger or ProCheck.

The 5TE sensor incorporates several features that also make it an excellent sensor for use with third party loggers. Customers may purchase the sensor with stripped and tinned wires (pigtail) for terminal connections. Visit www.decagon.com/support/literature to get extensive directions on how to integrate the 5TE sensor into third party loggers.

The 5TE sensor comes standard with a five meter cable. Customers may purchase sensors with custom cable lengths for an additional fee (on a per-foot fee basis). Decagon tests its digital sensor successfully with cable lengths up to 1000 meters (3200 ft.). Obtaining custom length cables eliminates the need for splicing the cable (a possible failure point).

Connecting to an Em50/Em50R Logger

Decagon designed the 5TE to work specifically with the Em50 data logger. Simply plug the 3.5 mm stereo plug connector directly into one of the five sensor ports. Next, configure the logger port for the 5TE and set the measurement interval.

Connecting to ECH2O Utility

Please check your software version to ensure it will support the 5TE. To update your software to the latest version, please visit Decagon’s software download site at www.decagon.com/support/downloads.

Note: You must use the ECH2O Utility, DataTrac 3 or a terminal program on your computer to download data from the logger to your computer.

5.1 Wiring

3.5 mm Stereo Plug Wiring



Figure 2: Stereo Plug

The following software support the 5TE sensor:

- ECH2O Utility 1.12 or greater
- ECH2O DataTrac 2.77 or greater

Connecting to a non-Decagon Logger

Customers may purchase 5TE sensors for use with non-Decagon data loggers. These sensors typically come configured with stripped and tinned (pigtail) lead wires for use with screw terminals. Refer to your distinct logger manual for details on wiring. Our Integrator's Guide gives detailed instructions on connecting the 5TE sensor to non-Decagon loggers. Please visit www.decagon.com/support/literature for the complete Integrator's Guide.

Pigtail End Wiring



Figure 3: Pigtail End Wiring

Connect the wires to the data logger as Figure 3 shows, with the

supply wire (white) connected to the excitation, the digital out wire (red) to a digital input, the bare ground wire to ground as illustrated below.

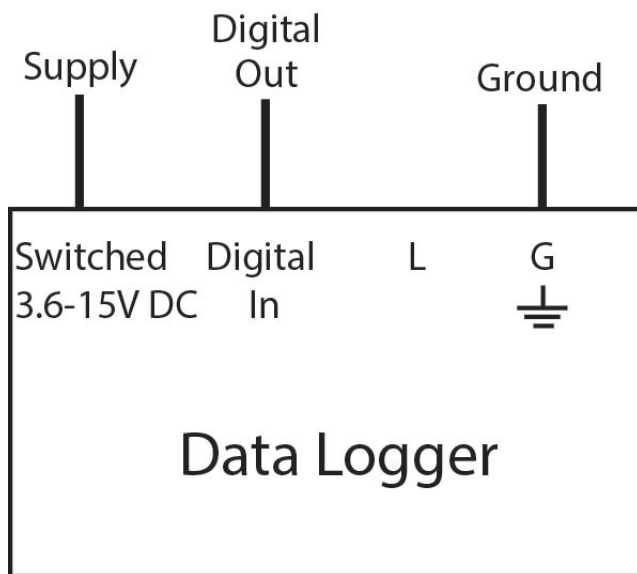


Figure 4: Pigtail End Wiring to Data Logger

Note: The acceptable range of excitation voltages is from 3.6 to 15 VDC. If you wish to read your Decagon sensor with the Campbell Scientific Data Loggers, you will need to power the sensors off of the switched 12V port.

If your 5TE is equipped with the standard 3.5 mm plug and you want to connect it to a non-Decagon data logger, you have two options. First, you can clip off the plug on the sensor cable, strip and tin the wires, and wire it directly into the data logger. This has the advantage of creating a direct connection with no chance of the sensor becoming unplugged; however, it cannot be easily used in the future with a Decagon readout unit or data logger.

The other option is to obtain an adapter cable from Decagon. The 3-wire sensor adapter cable has a connector for the sensor jack on one end, and three wires on the other end for connection to a data

logger (this type of wire is often referred to as a “pigtail adapter”). Both the stripped and tinned adapter cable wires have the same termination as seen above; the white wire is excitation, red is output, and the bare wire is ground.

5.2 Communication

The 5TE sensor communicates using two different methods, Serial (TTL) and SDI-12. Please visit www.decagon.com/support/literature for the complete Integrator’s Guide, which gives more detailed explanations and instructions. The 5TE sensor also communicates using SDI-12 protocol, a three-wire interface where all sensors are powered (white wire), grounded (bare wire), and communicate (red wire) on shared wires (for more info, go to www.sdi-12.org). If you plan on using SDI-12 for communication with the 5TE, please see our Integrator’s Guide at www.decagon.com/support/literature for detailed instructions.

6 Installing the Sensors

Decagon has a few helpful reminders to consider before beginning to use your sensor.

- Make sure the screw electrodes on the 5TE are clean before installing the sensors. See the sensor cleaning section at the end of the manual.
- If you are installing sensors in a lightning prone area with a grounded data logger, please see our Application Note at www.decagon.com/sensorappnotes.
- Decagon advises that you test the sensors with your data logging device and software before going to the field.

Before you select a site for installation, remember that the soil next to the sensor surface has the strongest influence on its readings. It is important to avoid air gaps or extremely compact soil around the sensor, which can skew readings. Do not install the 5TE next to large metal objects, which can attenuate the sensor electromagnetic field and distort output readings.

Because the sensors have gaps between their prongs, it is also important to consider the size of the media where you insert the sensor. It is possible to get sticks, bark, roots or other material stuck between the sensor prongs, which will adversely affect readings. Finally, be careful when inserting the sensors into dense soil, as the prongs can break if you apply excessive force when pushing them into the soil.

6.1 Procedure

Customers can insert the 5TE directly into growing media or soil. We have sharpened the tip of each prong to make it easier to push the sensor into the soil. Remember to be careful around the sharpened tips. The sensor needs to be completely covered by soil, as shown in Figure 5.

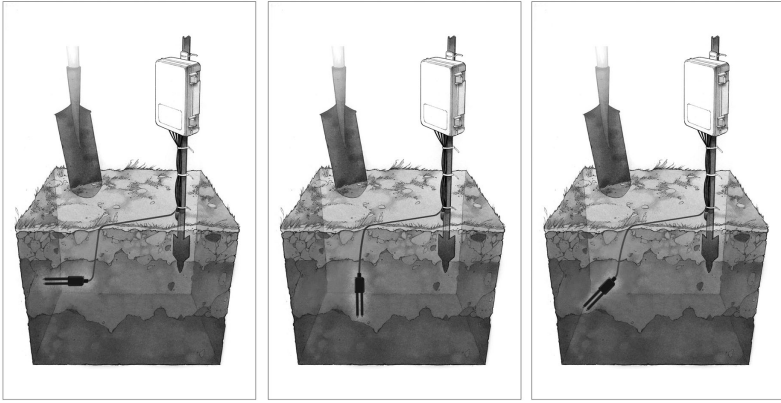


Figure 5: 5TE Proper Installation

The sensors may be difficult to insert into extremely compact or dry soil. If you have difficulty inserting the sensor, try loosening the soil somewhat or wetting the soil. Never pound the sensor into the soil, as you could damage the instrument.

6.1.1 Method 1: Horizontal Installation

Excavate a hole or trench a few centimeters deeper than the depth at which the sensor is to be installed. At the installation depth, shave off some soil from the vertical soil face exposing undisturbed soil. Insert the sensor into the undisturbed soil face until the entire sensing portion of the sensor. The tip of each prong has been sharpened to make it easier to push in the sensor. Be careful to avoid the sharp tips. Backfill the trench taking care to pack the soil back to natural bulk density around the black polyurethane portion of the sensor.

6.1.2 Method 2: Vertical Installation

Auger a 4-inch hole to the sensor installation depth. Insert the sensor into the undisturbed soil at the bottom of the auger hole using your hand or another implement to guide the sensor into the soil at the bottom of the hole. Many people have used a simple piece of PVC pipe with a notch cut in the end for the sensor to sit in, with

the sensor cable routed inside the pipe. After inserting the sensor, remove the installation device and backfill the hole taking care to pack the soil back to natural bulk density while not damaging the black plastic portion of the sensor or the sensor cable in the process.

6.2 Orientation

Users can orient Decagon sensors in any direction. Because the sensors have prongs instead of a blade (like the EC-10 and EC-20), you can place them in any orientation that meets your requirements.

6.3 Removing the Sensors

When removing the 5TE sensor, do not pull it by the cable. This could break the internal wires and cause the sensor to malfunction or not function at all.

6.4 Multiple Sensor Installation

The 5TE sensor makes electrical conductivity (EC) measurements by exciting one screw on the sensor and measuring the current that moves from that screw to the adjacent grounded screw. The distance between the screws is an important part of the EC calculation. If 5TE sensors are placed close together (within 20 cm), it is possible for some of the current that leaves the excited screw to pass through the nearby sensor ground screw, thus producing an erroneous sensor reading.

This problem occurs regardless of what logging system you are using if the ground wires are connected at all times. If you must have your sensors close together, (i.e. column experiments, etc.) consider a multiplexing option that would isolate the ground wires.

If you are installing sensors vertically at short depth intervals, do not bury them directly over the top of each other. Although at times the vertical distance may be less than 20 cm, the sensors can be staggered horizontally so they are not directly above each other,

thus meeting the distance requirement.

Campbell Scientific Programs

Because this sensor uses digital rather than analog communication, it requires special considerations when connecting to a Campbell Scientific data logger. Please visit our website at <http://www.decagon.com/csi-programs> to view sample Campbell Scientific programs.

7 Troubleshooting and Sensor Care

Before contacting Decagon about sensor malfunctions, follow the data logger and sensors troubleshooting steps 1 through 3.

7.1 Data Logger

1. Check to make sure the connections to the data logger are both correct and secure.
2. Ensure that your data logger batteries are not dead or weakened.
3. Check the configuration of your data logger in ECH2O Utility or ECH2O DataTrac to make sure you have selected 5TE.

7.2 Sensors

1. Ensure that your sensors are installed according to the “Installation” section of this manual.
2. Check sensor cables for nicks or cuts that could cause a malfunction.
3. Check your electrical conductivity sensor screws to ensure that they are not damaged or contaminated.

7.3 Sensor Cleaning

The EC measurement is very sensitive to the presence of nonconducting contamination on the screws, especially at high EC. The most common source of contamination is skin oil from handling the screws with bare hands. Figures 6 and 7 show the simplified electrical circuit resulting from a finger print on the screw in a low EC soil and high EC soil, respectively. It is apparent that in a low EC soil, the effects of contamination are relatively small, because the resistance in the soil dominates the total resistance. However, in a high EC soil, the effects of contamination become very large. This demonstrates

the need to keep the screws clean, especially when the sensor is to be used in high EC soil. Contamination of the screws during handling and shipping prevent the factory calibration from being valid past 8 dS/m, although the sensors will measure accurately at much higher EC with proper cleaning and calibration by the user.

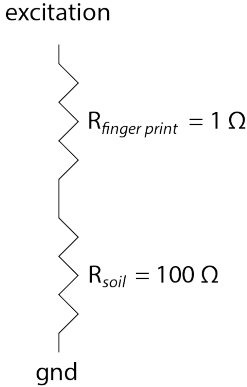


Figure 6: Simplified Circuit in Low EC Soil.

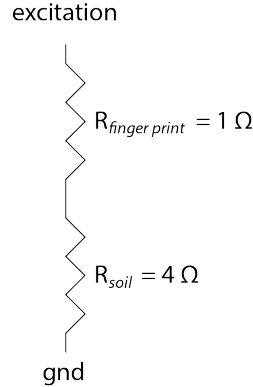


Figure 7: Simplified Circuit in High EC soil

Figure 6 shows a contaminated sensor in low EC (high resistance) soil, where $R^{total} = 101\Omega$ and a fingerprint causes a 1% error. Whereas Figure 7 demonstrates a simplified circuit for a contaminated sensor in high EC (low resistance) soil. $R^{total} = 5\Omega$, and here a fingerprint causes a 25% error.

7.4 Cleaning Method

1. Clean the screws using a mild detergent such as liquid dish soap and a non-abrasive sponge or cloth.

Note: Avoid detergents that contain lotions or moisturizers.

2. Rinse the sensor and screws thoroughly with tap or DI water.

Be sure not to touch the screws without gloved hands and never contact the sensors with any source of oil or other non-conducting residue.

8 Declaration of Conformity

Application of Council Directive:	2004/108/EC and 2011/65/EU
Standards to which conformity is declared:	EN 61326-1:2013 and EN 50581:2012
Manufacturer's Name:	Decagon Devices, Inc. 2365 NE Hopkins Ct. Pullman, WA 99163 USA
Type of Equipment:	Dielectric Soil Moisture Sensor
Model Number:	5TE
Year of First Manufacture:	2005

This is to certify that the 5TE dielectric soil moisture sensor, manufactured by Decagon Devices, Inc., a corporation based in Pullman, Washington, USA meets or exceeds the standards for CE compliance as per the Council Directives noted above. All instruments are built at the factory at Decagon and pertinent testing documentation is freely available for verification.

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