DECAGON DEVICES

Application Note

# Calibrating ECH$_2$O Soil Moisture Sensors

Douglas R. Cobos, Ph.D.

## Introduction

Decagon's ECH$_2$O probes measure the volumetric water content of the soil by measuring the dielectric constant of the soil, which is a strong function of water content. However, not all soils have identical electrical properties. Due to variations in soil texture and salinity, the generic mineral calibration for ECH$_2$O probes results in approximately ± 3-4% accuracy for most medium to fine textured mineral soils, and the accuracy for coarse-textured and high-salinity soils can vary up to ± 10% (see Table 1). However, accuracy increases to ± 1-2% for all soils with soil-specific calibration. Decagon recommends that ECH$_2$O probe users conduct a soil-specific calibration for best possible accuracy in volumetric water content measurements. Recent tests by independent researchers (Czarnomski et al., 2005) indicate that soil-specific calibration of ECH$_2$O probes achieves performance results similar to that of TDR instruments - at a fraction of the price. Note that the resolution, precision, repeatability, and probe to probe agreement of the ECH$_2$O probes are excellent, so the soil specific calibration of one probe can be applied to all other probes of that type in that particular soil. The purpose of this application note is to provide a step-by-step guide for performing a soil specific calibration on ECH$_2$O probes.

Table 1. Typical accuracy for ECH$_2$O probes in various growth media with generic calibration and with soil specific calibration.

| **ECH$_2$O probe model** | **Accuracy with generic calibration** | | | **Accuracy with soil-specific calibration** |
|---|---|---|---|---|
| | Fine textured mineral soils, electrical conductivity <0.5 dS/m | All mineral soils, all electrical conductivities[4] | Other growth media (potting soil, etc.) | All soil/medium types |
| EC-5 | ±3% | ±3% | 5%[3] | ±1-2% |
| EC-10 | ±4% | ±10%[1] | N/A[2] | ±1-2% |
| EC-20 | ±4% | ±10%[1] | N/A[2] | ±1-2% |
| EA-10 | ±4% | ±10%[1] | N/A[2] | ±1-2% |
| ECH$_2$O TE | ±3% | ±3% | ±5%[3] | ±1-2% |

[1] Sandy soils with especially high EC can have highly variable calibrations and can yield accuracy worse than ± 10% in some cases.

[2] The factory calibration will result in very poor accuracy in non-mineral soils. A medium-specific calibration must be performed in non-soil media.

[3] Decagon maintains a library of ECH2O-TE calibrations for various growth media that we have tested. If your particular medium isn't in the library, use this application note to conduct a soil specific calibration or our calibration service can generate a calibration for you. Contact soils@decagon.com to check calibration availability.

[4] Tests have been conducted on soils up to saturated electrical conductivity (EC$_s$) of 10 dS/m with good calibration results. We have found that soils with 30 dS/m or more will shift the calibration considerably.

## Calibration Method

$ECH_2O$ calibration generally follows the standard procedure for calibrating capacitance probes outlined by Starr and Palineanu (2002). The following is a step-by-step instruction guide for performing a soil specific calibration.

## 1. Equipment needed

1.1. Shovel and bulk soil container (1 shovel, 1 container for each soil type) – for field soil collection and air drying soil.

1.2. Calibration container (1). The calibration container should allow you to pack the soil back to the field bulk density while maintaining at least 5 cm of soil depth. It is best if the container is relatively rigid, and allows clear access to the soil surface.

1.3. $ECH_2O$ probe and data acquisition system (1 each)
  1.3.1. $ECH_2O$ probe output is very similar among probes of the same type. So, you can calibrate with a single probe and apply that calibration to other probes of that type in your soil and maintain excellent accuracy.
  1.3.2. Use whatever data acquisition system that you are planning to use in the field ($ECH_2O$ Check, Em50, Em5b, Campbell Scientific datalogger, etc.).

1.4. Volumetric soil sampler (1)
  1.4.1. To perform an $ECH_2O$ probe calibration you must have a volumetric soil sampler, which is used to sample known volumes of soil from the calibration container in order to determine volumetric water content. This can either be a commercial soil sampler or a homemade sampler. The only requirement for the sampler is that you can collect a soil sample of known volume without changing the soil bulk density.
  1.4.2. If you don't have a sampler, we recommend cutting a 3 - 5 cm long section of metal conduit or other small diameter (1.5 - 2.5 cm) metal or thin walled, rigid plastic tubing. Deburr both ends of the tubing, and sharpen one end for easy insertion into the soil.
  1.4.3. Precisely measure the length and diameter of the sampler, and calculate the volume ($\pi r^2 h$).

1.5. Soil drying containers (5-7 per soil type)
  1.5.1. The drying container can be any container that is suitable for oven drying and has a sealable lid (soil sampling tin, baby food jar).
  1.5.2. Measure the mass of each of the clean, dry soil drying containers before adding soil to them. Write down the tare mass in Table 2.

1.6. Scale or mass balance (1) – The scale must have resolution of 0.01 g or better for best possible soil specific calibration.

1.7. Drying oven (1) – Any oven that will maintain a relatively stable temperature of 105 – 110 C will work.

## 2. Soil sample collection

2.1. Collect approximately 4 liters (1 gallon) of bulk soil.

2.2. Be sure that the soil is from the area/depth where you wish to measure with your $ECH_2O$ probes.

2.3. You may wish to measure the field bulk density of the soil when you collect your sample.
  2.3.1. Use your volumetric soil sampler to collect several soil cores of undisturbed soil.
  2.3.2. Since you've used a volumetric sampler, you know the volume of the soil sample ($V_{soil}$).

- 2.3.3. Oven dry the soil cores and measure the mass of the dry soil ($m_{dry}$).
- 2.3.4. Use equation 4 below to calculate the bulk density of the soil.

## 3. Soil Preparation

3.1. Air dry the soil. Air drying is quickest if the soil is spread in a thin layer and air is moved over the soil.

3.2. Remove large objects from the soil.

- 3.2.1. The presence of large rocks or other objects can complicate the calibration process. We suggest breaking up large clods and running the soil through a 5 mm sieve before proceeding.
- 3.2.2. In some materials (e.g. compost, mulch), it will not be possible to remove large particulates without significantly altering the nature of the material.

## 4. Calibration

4.1. Pack the soil into the calibration container at approximately the field bulk density.

- 4.1.1. It is generally necessary to add the soil in layers, packing each layer before adding the next.
- 4.1.2. For the EC-10, EA-10, and EC-20 probes, only pack a little over half of the soil into the container before inserting the probe.
- 4.1.3. For the EC-5 and ECH$_2$O TE, pack the full soil volume into the container.

4.2. Insert the ECH$_2$O probe (EC-10, EA-10, EC-20).

- 4.2.1. Use your finger or a small diameter tool to dig a shallow trench in the half-full soil container the full length of the probe.
- 4.2.2. Set the probe on edge in the trench you just made. The long axis of the probe should be horizontal, and the flat plane should be vertical.
- 4.2.3. Add a small amount of soil over the probe.
- 4.2.4. Use two fingers to pack the soil evenly on both sides of the probe. Our standard method is to pack the soil around the probe with the middle and index finger 7-8 times per soil layer. It is very important that the soil and probe are in perfect contact (no gaps around the probe).
- 4.2.5. Repeat 4.2.3 and 4.2.4 four or five times until the probe is completely buried in the soil with desired bulk density.
- 4.2.6. Add the rest of the soil in layers as described in 4.1.1

4.3. Insert the ECH$_2$O probe (EC-5, ECH$_2$O TE).

- 4.3.1. The EC-5 and ECH$_2$O TE can be inserted vertically directly into the full soil container.
- 4.3.2. Be sure to insert the probe tines in a straight line so as not to introduce any air gaps between the probe tines and the soil.
- 4.3.3. Insert the probe fully into the soil. This includes the black plastic base of the probe. If you cannot insert the black plastic portion fully into the soil, insert the probe as far as possible, and take soil from part of the and pack it around the remaining portion of the probe base.

4.4. **Important note:** The probe should be surrounded by continuous soil for a radius of at least 5 cm from the flat sensing portion of the probe.

4.5. Take a probe reading.

- 4.5.1. If you are using non-Decagon data acquisition equipment, be sure that you are exciting the probe with the same excitation voltage that you will use in the field

4.5.2. Collect the raw data from the probe (no calibration applied). For the EM 50 and EM 5b loggers, this will be raw counts. For Campbell Scientific loggers, this will be mV.
4.5.3. It is a good idea to repeat 4.2 - 4.5 once or twice to be sure that you are achieving repeatable insertion quality. There will generally be some small variability (a few raw counts or mV), so an average reading can be taken.
4.5.4. Record the probe reading in Table 2.

4.6. If you are calibrating multiple EC-10, EA-10, and EC-20, each probe must be repacked following 4.2 and 4.5 to ensure an accurate readings

4.7. Collect a volumetric soil sample.
4.7.1. Without removing the ECH$_2$O probe, insert the volumetric soil sampler fully into the undisturbed soil near the probe.
4.7.2. Remove the sampler, making sure that the soil core inside is intact. Shave excess soil from the end(s) with a flat edge, and re-fill any small voids that may have occurred.
4.7.3. Place the entire soil core into a drying container and replace the lid. Any water loss from the soil between sampling and the first weighing introduces error to the volumetric water content calculation.
4.7.4. Repeat 4.6.1 - 4.6.3 at least once. This helps to reduce the effects of spatial variability in your sample.
4.8. Measure the mass of the wet soil + container (no lid) – record the mass in Table 2.

4.9. Wet the calibration soil.
4.9.1. Add 200 – 300 mL of water to the soil as evenly as possible
4.9.2. Thoroughly mix the soil with your hands or a trowel until the mixture is again homogenous.

4.10. Repeat 4.1 to 4.8 until the soil nears saturation. This generally yields 5-7 calibration points.

4.11. Dry the volumetric soil samples
4.11.1. Place all of the already-weighed, moist samples into the 105 C oven for 24 hours.
4.11.2. Note that soils with high organic matter content may lose significant volatile organics if dried at 105 C, leading to error in the calibration. We recommend drying these soils at 60 – 70 C for at least 48 hours.

4.12. Weigh the dry soil.
4.12.1. Remove the soil drying containers from the oven and replace covers while still hot
4.12.2. Allow the soil and containers to cool
4.12.3. Measure the mass of the dry soil + containers (without lids).
4.12.4. Enter the values into Table 2.

Table 2. Example data collection table for soil specific $ECH_2O$ probe calibration.

| Sample number | Avg. probe reading (raw counts or mV) | Drying container tare mass (g) | Sample volume ($cm^3$) | mass of container + moist soil (g) | mass of container + dry soil (g) |
|---|---|---|---|---|---|
| 1 | 664 | 70.605 | 15.31 | 94.836 | 94.215 |
| 2 | 764 | 72.245 | 15.31 | 96.433 | 95.194 |
| 3 | 902 | 71.713 | 15.31 | 96.923 | 94.785 |
| 4 | 1030 | 74.45 | 15.31 | 101.979 | 98.834 |
| 5 | 1318 | 70.997 | 15.31 | 100.402 | 95.873 |
| 6 | 1374 | 71.48 | 15.31 | 101.060 | 95.886 |

## 5. Calculations

The volumetric water content is defined as the volume of water per volume of bulk soil:

$$\theta = V_w/V_t \tag{1}$$

Where $\theta$ is volumetric water content ($cm^3/cm^3$), $V_w$ is the volume of water ($cm^3$) and $V_t$ is the total volume of bulk soil sample ($cm^3$). You already know $V_t$ of your sample, because you used a volumetric sampler to collect your soils samples (see section 1.4). To find $V_w$, we calculate the volume of the water that is lost from the soil sample during oven drying:

$$m_w = m_{wet} - m_{dry} \tag{2}$$

$$V_w = m_w/\rho_w \tag{3}$$

Where $m_w$ is the mass of water, $m_{wet}$ is the mass of moist soil (g), $m_{dry}$ is the mass of the dry soil, and $\rho_w$ is the density of water (1 $g/cm^3$). In addition to the volumetric water content, the bulk density of the soil sample can also be calculated. Bulk density ($\rho_b$) is defined as the density of dry soil ($g/cm^3$):

$$\rho_b = m_{dry}/V_{soil} \tag{4}$$

The calculations above are most easily done in a spreadsheet program such as MS Excel. Table 3 shows an Excel spreadsheet with the data from Table 2, and the above calculations performed. The cell operations used to perform the calculations are shown in Row 3.

The output of the $ECH_2O$ probes is not very sensitive to small differences in soil bulk density. However, if the bulk density of the soil during calibration is radically different from that of your field soil, you may introduce error into your calibration. If you measured the field bulk density as described in section 2.3, you can compare the field bulk density with the bulk densities achieved in your calibration container. If the bulk densities are different by more than about 5%, you should consider repeating the calibration while packing the soil to more realistic bulk densities.

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Table 3. Excel spreadsheet with example calibration data. Note that Row 2 shows the variables names used in calculation section, and Row 3 shows the cell operations used to calculate VWC from the calibration data.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | sample number | probe output (Raw counts) | Jar mass (g) | sample volume (cm$^3$) | wet soil mass + container (g) | dry soil mass + container (g) | Mass & volume of water (cm$^3$) | Dry soil mass (g) | soil bulk density (g/cm$^3$) | VWC (cm$^3$/cm$^3$) |
| 2 | | | | $\mathbf{V_t}$ | | | $\mathbf{(m_w, V_w)}$ | $\mathbf{m_{dry}}$ | $\boldsymbol{\rho_b}$ | $\boldsymbol{\theta}$ |
| 3 | | | | | | | =E3-F3 | =F3-C3 | =H3/D3 | =G3/D3 |
| 4 | 1 | 664 | 70.605 | 15.31 | 94.836 | 94.215 | 0.621 | 23.610 | 1.54 | 0.0406 |
| 5 | 2 | 764 | 72.245 | 15.31 | 96.433 | 95.194 | 1.239 | 22.949 | 1.50 | 0.0809 |
| 6 | 3 | 902 | 71.713 | 15.31 | 96.923 | 94.785 | 2.138 | 23.072 | 1.51 | 0.1396 |
| 7 | 4 | 1030 | 74.45 | 15.31 | 101.979 | 98.834 | 3.145 | 24.384 | 1.59 | 0.2054 |
| 8 | 5 | 1318 | 70.997 | 15.31 | 100.402 | 95.873 | 4.529 | 24.876 | 1.62 | 0.2958 |
| 9 | 6 | 1374 | 71.48 | 15.31 | 101.060 | 95.886 | 5.174 | 24.406 | 1.59 | 0.3379 |

## 6. Finding and using the calibration function

If the above calculations are performed in a spreadsheet program, then finding the calibration function is quite easy. Simply make a scatter plot with the probe output on the X-axis, and the calculated VWC on the Y-axis (Figure 1). Then use the trendline or curve fitting function to construct a mathematical model of the relationship. This relationship is often linear as shown below, but is sometimes is best fit with a quadratic equation, especially in soils with high organic matter content.

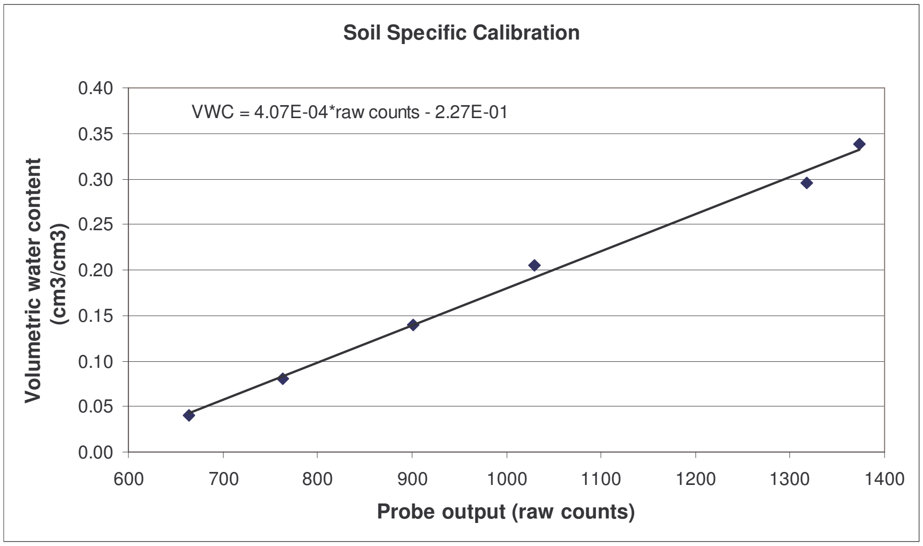

*Figure 1. Plot of example calibration data. The soil specific calibration equation is shown in the upper left corner of the graph area.*

Once you have constructed your calibration function, you need to apply it to the ECH$_2$O probe data that you collect. When logging data with the EM 50 and EM 5b dataloggers, you should apply this equation to the raw data that you download from the logger. If you are using the DataTrac software package, you can apply the calibration function under the setup tab. If you are using Campbell Scientific dataloggers, you can apply the calibration in your datalogger program or during post processing.

## References

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