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This equipment is warranted by CAMPBELL SCIENTIFIC (CANADA) CORP. ("CSC") to be free from defects in materials and workmanship under normal use and service for twelve (12) months from date of shipment unless specified otherwise. ***** Batteries are not warranted. ***** CSC's obligation under this warranty is limited to repairing or replacing (at CSC's option) defective products. The customer shall assume all costs of removing, reinstalling, and shipping defective products to CSC. CSC will return such products by surface carrier prepaid. This warranty shall not apply to any CSC products which have been subjected to modification, misuse, neglect, accidents of nature, or shipping damage. This warranty is in lieu of all other warranties, expressed or implied, including warranties of merchantability or fitness for a particular purpose. CSC is not liable for special, indirect, incidental, or consequential damages.

Products may not be returned without prior authorization. To obtain a Return Merchandise Authorization (RMA), contact CAMPBELL SCIENTIFIC (CANADA) CORP., at (780) 454-2505. An RMA number will be issued in order to facilitate Repair Personnel in identifying an instrument upon arrival. Please write this number clearly on the outside of the shipping container. Include description of symptoms and all pertinent details.

CAMPBELL SCIENTIFIC (CANADA) CORP. does not accept collect calls.

Non-warranty products returned for repair should be accompanied by a purchase order to cover repair costs.
PLEASE READ FIRST

About this manual

Please note that this manual was originally produced by Campbell Scientific Inc. (CSI) primarily for the US market. Some spellings, weights and measures may reflect this origin.

Some useful conversion factors:

<table>
<thead>
<tr>
<th>Area:</th>
<th>1 in² (square inch) = 645 mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length:</td>
<td>1 in. (inch) = 25.4 mm</td>
</tr>
<tr>
<td></td>
<td>1 ft (foot) = 304.8 mm</td>
</tr>
<tr>
<td></td>
<td>1 yard = 0.914 m</td>
</tr>
<tr>
<td></td>
<td>1 mile = 1.609 km</td>
</tr>
<tr>
<td>Mass:</td>
<td>1 oz. (ounce) = 28.35 g</td>
</tr>
<tr>
<td></td>
<td>1 lb (pound weight) = 0.454 kg</td>
</tr>
<tr>
<td>Pressure:</td>
<td>1 psi (lb/in²) = 68.95 mb</td>
</tr>
<tr>
<td>Volume:</td>
<td>1 US gallon = 3.785 litres</td>
</tr>
</tbody>
</table>

In addition, part ordering numbers may vary. For example, the CABLE5CBL is a CSI part number and known as a FIN5COND at Campbell Scientific Canada (CSC). CSC Technical Support will be pleased to assist with any questions.

About sensor wiring

Please note that certain sensor configurations may require a user supplied jumper wire. It is recommended to review the sensor configuration requirements for your application and supply the jumper wire is necessary.
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1. Introduction

This document presents descriptions and instructions for Campbell Scientific Time Domain Reflectometry (TDR) probes and includes some TDR principles. Consult the TDR100 operating manual for comprehensive TDR instructions.

A single TDR probe can be connected directly to the TDR100 or multiple probes connected via the SDMX50-series Coaxial Multiplexers.

Before using the TDR probes, please study:

- Section 2, Cautionary Statements
- Section 3, Initial Inspection

2. Cautionary Statements

- Care should be taken when opening the shipping package to not damage or cut the cable jacket. If damage to the cable is suspected, consult with a Campbell Scientific application engineer.

- The CS605 and CS610 are shipped with rubber caps covering the sharp ends of the rods. Remove the three caps before use.

- The TDR100 is sensitive to electrostatic discharge damage. Avoid touching the center conductor of the panel BNC connector or the center rod of TDR probes connected to the TDR100.

3. Initial Inspection

- Upon receipt of a TDR probe, inspect the packaging and contents for damage. File damage claims with the shipping company.

- The model number and cable length are printed on a label at the connection end of the cable. Check this information against the shipping documents to ensure the correct product and cable length are received.

4. Overview

TDR probes are the sensors of the TDR measurement system and are inserted or buried in the medium to be measured. The probes are a wave guide extension on the end of coaxial cable. Reflections of the applied signal along the waveguide will occur where there are impedance changes. The impedance value is related to the geometrical configuration of the probe (size and spacing of rods) and also is inversely related to the dielectric constant of the surrounding material. A change in volumetric water content of the medium surrounding the probe causes a change in the dielectric constant. This is seen
as a change in probe impedance which affects the shape of the reflection. The shape of the reflection contains information used to determine water content and soil bulk electrical conductivity.

5. Specifications

5.1 Physical Description

<table>
<thead>
<tr>
<th>Probe Model</th>
<th>Rods</th>
<th>Probe Head</th>
<th>Cable Type</th>
<th>Maximum Soil Bulk Electrical Conductivity</th>
<th>Maximum Cable Length (measured from the tips of the probe’s rods to the TDR100 Reflectometer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS605</td>
<td>length 30.0 cm diameter 0.475 cm</td>
<td>length width thickness 10.8 cm 7.0 cm 1.9 cm</td>
<td>RG58</td>
<td>1.4 dS/m</td>
<td>15 m</td>
</tr>
<tr>
<td>CS610</td>
<td>length 30.0 cm diameter 0.475 cm</td>
<td>length width thickness 10.8 cm 7.0 cm 1.9 cm</td>
<td>RG8 low loss</td>
<td>1.4 dS/m</td>
<td>25 m</td>
</tr>
<tr>
<td>CS630</td>
<td>length 15.0 cm diameter 0.318 cm</td>
<td>length width thickness 5.75 cm 4.0 cm 1.25 cm</td>
<td>RG58</td>
<td>3.5 dS/m</td>
<td>15 m</td>
</tr>
<tr>
<td>CS635</td>
<td>length 15.0 cm diameter 0.318 cm</td>
<td>length width thickness 5.75 cm 4.0 cm 1.25 cm</td>
<td>LMR-200 low loss</td>
<td>3.5 dS/m</td>
<td>25 m</td>
</tr>
<tr>
<td>CS640</td>
<td>length 7.5 cm diameter 0.159 cm</td>
<td>length width thickness 4.5 cm 2.2 cm 1.0 cm</td>
<td>RG58</td>
<td>5.0 dS/m</td>
<td>15 m</td>
</tr>
<tr>
<td>CS645</td>
<td>length 7.5 cm diameter 0.159 cm</td>
<td>length width thickness 4.5 cm 2.2 cm 1.0 cm</td>
<td>LMR-200 low loss</td>
<td>5.0 dS/m</td>
<td>25 m</td>
</tr>
</tbody>
</table>

5.2 Measurement Parameters

<table>
<thead>
<tr>
<th>Probe Model</th>
<th>Probe Offset (meters)</th>
<th>Probe Constant for Electrical Conductivity (EC) Measurement, Kp (using this constant will provide EC in siemens/meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS605 and CS610</td>
<td>0.090</td>
<td>1.74</td>
</tr>
<tr>
<td>CS630 and CS635</td>
<td>0.052</td>
<td>3.36</td>
</tr>
<tr>
<td>CS640 and CS645</td>
<td>0.035</td>
<td>6.40</td>
</tr>
</tbody>
</table>
5.3 **Electromagnetic Compatibility**

All TDR probes are compliant with performance criteria available upon request. RF emissions are below EN55022 limit.

6. **Installation**

TDR probes can be installed in any orientation: horizontally, vertically, or at an angle to the surface. The measured water content is the integral or average of the water content over the length of the probe rods. The probe rods should be completely surrounded by the soil or other media being measured. If portions of the probe rods are exposed to air, the algorithm for analyzing the waveform reflection may not be able to correctly locate the beginning and end of the probe rods.

Care must be exercised when inserting probe rods into the soil to minimize soil compaction around the rods. Compaction can leave air voids along the length of the rods. The region adjacent to the rod is the most sensitive so voids near the rods can be a significant source of error.

After the soil is disturbed for probe installation, most soils will experience rejuvenation of the soil structure with wetting/drying cycle and freeze/thaw cycles.

TDR probes can be buried or inserted into the soil. The CS605G Installation Guide should be used when inserting the CS605 and CS610 into the material being measured. A guide is generally not needed for the smaller diameter probes.

7. **Operation**

7.1 **Probe Offset for Water Content Measurement**

A portion of the TDR probe rods is surrounded by the probe head material and is not exposed to the material being measured. Probe offset is used to correct for this. TABLE 5-2 lists offset values for probes manufactured by Campbell Scientific. These values are entered in the datalogger instruction or in the PC-TDR software.

7.1.1 **Calculating Probe Offset**

Probe offset can be calculated using information from PC-TDR. The probe rods are immersed in water of known temperature, algorithm values are collected in the terminal emulator mode of PC-TDR, and simple calculations provide custom offset values. See Appendix A, *Discussion of TDR Probe Offset and a Simple Laboratory Method for Calculation*, for calculation method.

The values listed in TABLE 5-2 were determined using TDR probes with short cables. The shape of the waveform reflection is affected as cable length increases, and this can introduce error into the water content measurement. Using probe offsets determined by the method described in Appendix A, *Discussion of TDR Probe Offset and a Simple Laboratory Method for*
Calculation, with all cabling from TDR100 to probe in place will compensate for the cable losses. Probe offset values obtained this way will be greater than those listed in TABLE 5-2.

7.2 Probe Constant for Electrical Conductivity Measurement

The electrical conductivity measurement requires a probe constant to account for probe geometry. The probe constant is commonly referred as \( K_p \). The probe constant is entered as a multiplier in the datalogger instruction for TDR100 EC measurement. \( K_p \) is set in PC-TDR using Settings/Calibration Functions/Bulk Electrical Conductivity. Using the \( K_p \) values in TABLE 5-2 will give electrical conductivity in the units siemens/meter. For the more common units of decisiemens/meter, multiply the TABLE 5-2 \( K_p \) values by 10.

Probe constant can be calculated using PC-TDR. Selecting Settings/Calibration Functions/Bulk Electrical Conductivity will present a button to Measure Cell Constant. The method requires submersion of the TDR probe rods in de-ionized water of known temperature. See PC-TDR HELP for simple instructions. It is recommended to make several \( K_p \) determinations and use the average value.

Probe constant can also be calculated using the method presented in Appendix B, Correcting Electrical Conductivity Measurements. This method accounts for signal losses in system cabling and multiplexers.

7.2.1 Electrical Conductivity Error from Attenuation

Attenuation of the applied and reflected signal in the cable and multiplexers will affect the accuracy of the electrical conductivity measurement. For accurate electrical conductivity measurements, this attenuation must be accounted for.

A paper published by Castiglione and Shouse (2003) describes the error and a method to account for the error. The method requires electrical conductivity measurement with the probes in air and with the rods shorted with all system components in place (cable and multiplexers).

Appendix B, Correcting Electrical Conductivity Measurements, presents a summary of the Castiglione and Shouse (2003) method and an adaptation of the method for the TDR100 system.

7.3 Water Content Measurement Error from Cable

The determination of water content using the TDR system relies on the evaluation of a pulse reflection from the TDR probe. The pulse generated by the TDR100 and its reflections are subject to distortion during travel between the TDR100 and the TDR probe. The cable connecting the probe to the reflectometer has a characteristic impedance resulting in both resistive and reactive losses. Distortion of the waveform caused by cable impedance can introduce error into the water content determination.

FIGURE 7-1 presents waveforms collected from a 3-rod probe (CS610) for various cable lengths. As cable length increases, the rise time and the amplitude of the reflection are affected. The slopes and extrema used by the
The signal at the probe will be attenuated when ionic conduction occurs in the soil solution. This inherent attenuation is used in TDR measurements to determine soil electrical conductivity as described by equation [5] in the TDR100 manual. The presence of ions in the soil solution provides a path for electrical conduction between TDR probe rods. The attenuation of the signal
can affect the accuracy and resolution of water content measurements. FIGURE 7-2 presents a series of waveforms when a solution with an electrical conductivity of 1.0 dS m\(^{-1}\) is added to a soil which has essentially no salt present. FIGURE 7-3 shows data for solution with high electrical conductivity.

**FIGURE 7-2.** Waveforms collected in a sandy loam using CS610 probe with RG8 connecting cable. Volumetric water content values are 10, 16, 18, 21 and 25%. Solution electrical conductivity is 1.0 dS m\(^{-1}\).

**FIGURE 7-3.** Waveforms collected in a sandy loam using CS610 probe with RG8 connecting cable. Volumetric water content values are 10, 18, 26, 30 and 37%. Solution electrical conductivity is 10.2 dS m\(^{-1}\).
The combined effect of long cable runs and high soil electrical conductivity must be considered when TDR measurements are taken.

8. References


Appendix A. Discussion of TDR Probe Offset and a Simple Laboratory Method for Calculation

A.1 Discussion of Probe Offset

Probe offset accounts for the segment of the TDR probe rods that is part of the probe head and is not exposed to the media surrounding the probe rods. The location of the beginning of the probe that is calculated in the TDR100 operating system is the point along the cable where the transition from the 50 ohm cable to the TDR probe impedance occurs. The distance from this transition to the point where the rods come out of the probe head is constant and can be accounted for.

The TDR100 operating system uses the following equation to calculate the ratio of apparent rod length to actual rod length, \( \frac{L_a}{L} \). This ratio is equal to the square root of dielectric permittivity, \( \sqrt{\varepsilon} \).

\[
\frac{L_a}{L} = \frac{\text{end} - \text{start} - \text{ProbeOff}}{V_p} - \frac{\text{ProbeOff}}{L}
\]  

[A1]

| \( L_a \) | apparent length (m) |
| \( L \) | actual rod length (m) |
| \( V_p \) | relative propagation velocity (1.0) |
| \( \text{ProbeOff} \) | probe offset (m) |
| \( \text{start} \) | distance into window for beginning of rods (m) |
| \( \text{end} \) | distance into window for end of rods (m) |

To examine the sensitivity of \( \frac{L_a}{L} \) to probe offset, multiply equation [A1] by \( L \) and take the 1st derivative of \( L_a \) with respect to probe offset.

\[
\frac{d}{d(\text{ProbeOff})} \left( \frac{\text{end} - \text{start}}{V_p} - \frac{\text{ProbeOff}}{L} \right) = -1
\]  

[A2]

The sensitivity of the apparent length measurement, \( L_a \), is directly related to probe offset. A probe offset difference of 0.005 changes \( L_a \) by –0.005. The water content error for saturated soil is 0.16% volumetric water content. In very dry soil the error is 0.20%. There is a slight dependence of probe offset on water content but the amount is within the resolution of the water content measurement.
A.2 The Compounding Effect of Signal Attenuation in Connecting Cables

The probe offset values provided in the operating manual were calculated from measurements in the Campbell Scientific soils laboratory. The method is described below. The length of cable for the laboratory calculations was 3 meters or less. As cable length increases, signal loss occurs in both amplitude and bandwidth. As a result of bandwidth loss, the slope of the waveform at the beginning of the probe decreases with increasing cable length. The probe start is determined from the intersection of a line tangent to the waveform at the steepest point and of a line that is essentially horizontal. See FIGURE A-1. The probe offset correction identifies the location where the rods exit the probe head.

The slope of the tangent line decreases as cable length increases, and the intersection of the two lines will shift in the direction of greater apparent probe rod length.

Calculating the probe offset using the method described below and with all cables and multiplexers in place will optimize the accuracy of water content measurements.
A.3 Method for Calculating Probe Offset Using Information from the Terminal Mode of PC-TDR

Letting $V_p = 1$ and solving [1] for ProbeOffset gives:

\[ \text{ProbeOffset} = \text{end} - \text{start} - L_a \]  \[ A3 \]

The start and end distance values are determined by an algorithm in the TDR100 operating system. The apparent length, $L_a$, excluding the offset, is related to actual rod length and permittivity by:

\[ L_a := L \cdot \sqrt{\varepsilon(T)} \]  \[ A4 \]

The rod length, $L$, is the physical length of the rods (m). For 3-rod TDR probes with longer outer rods, the length of the outer rods is used.

The dielectric permittivity of water can be calculated from water temperature using:

\[ \varepsilon(T) := 78.54 \left[ -4.5791 \times 10^{-3} \cdot (T - 25) + 119 \times 10^{-5} \cdot (T - 25)^2 - 2.8 \times 10^{-8} \cdot (T - 25)^3 \right] \]  \[ A5 \]

TABLE A-1 contains dielectric permittivities for a typical range of temperatures and may be used in lieu of equation [A5]. Substituting the calculation of $L_a$ using equations [A4] and [A5] into equation [A3] leaves the end and start distances as the only unknowns. These values can be acquired directly from the TDR100 algorithm by using the terminal emulator mode of PC-TDR.

A.3.1 Procedure for Calculating Probe Offset

Connect all cabling and multiplexers to be used for field or laboratory measurements.

Immerse the TDR probe rods in DI or tap water. The container must be large enough to ensure rods are at least 5 cm from container walls.

Use PC-TDR as follows:

1. Enter values for Waveform parameters. Suggested values are: Average = 4, Points = 251. Relative propagation velocity, $V_p$, must be 1. Choice of start point and waveform length depends on the length of the cable and the actual probe rod length. There should be about 0.5 meters before the probe, enough distance for probe apparent length in water (approximately 9 times rod length), and enough distance for the waveform past the end of the probe. The distance for the end can be approximated as 3 times rod length.

2. Enter the value for Probe Rod Length in meters and set Probe Offset to 0 m.

3. Click the Water Content button to send the values to the TDR100 and to have it calculate $L_a/L$ and provide start and end values.
4. Enter **Terminal Mode** using *Options/Terminal Emulator*.

5. Press Enter until > appears (the line commands are not case sensitive)

6. Type GVAR then Enter.

7. It is recommended that step 6 be repeated several times and that the average values of Start and End be used for following calculations.

   GVAR returns the uncorrected Start and End. These values must be converted to distance from index values. This is done as follows:

   \[
   \text{start distance} = \frac{\text{start}}{\text{datapoints} - 1} \times \text{WaveformLength} \\
   \text{end distance} = \frac{\text{end}}{\text{datapoints} - 1} \times \text{WaveformLength}
   \]

   Equations [A3] and [A4] are then used to calculate probe offset.

**A.3.2 An Example Using CS605**

- Measured TDR probe rod length: \( L = 0.3 \text{ m} \).
- Measure temperature of water in column \( T = 24.4^\circ \text{C} \).
- Determine actual dielectric permittivity of water using following equation or values in TABLE A-1.

\[
\varepsilon(T) = 78.54 \left[ 1 - 4.5791 \times 10^{-3} \cdot (T - 25) + 1.19 \times 10^{-3} \cdot (T - 25)^2 - 2.8 \times 10^{-8} \cdot (T - 25)^3 \right]
\]

\( \varepsilon(T) = 78.76 \)

\( La = L \cdot \sqrt{\varepsilon(T)} \)

\( La = 2.66 \text{ m} \)

- Waveform parameters for PC-TDR

  \( \text{WindowLength} = 5 \text{ m} \quad \text{datapoints} = 251 \quad V_p = 1.0 \)

  \( \text{Probe length} = 0.3 \text{ m} \quad \text{Probe offset} = 0 \text{ m} \)

- Start and end index values from terminal emulator mode of PC-TDR as described above

  \( \text{start}_{\text{index}} = 32.44 \quad \text{end}_{\text{index}} = 169.87 \)

- Converting waveform index to apparent distance

  \( \text{start}_{\text{distance}} = \frac{\text{start}_{\text{index}}}{\text{datapoints} - 1} \times \text{WindowLength} \)
end\textsubscript{distance} := \frac{\text{end}\textsubscript{index}}{\text{datapoints} - 1} \cdot \text{WindowLength}

\text{start}\text{distance} = 0.65 \quad \text{end}\text{distance} = 3.4

\text{ProbeOffset} := \frac{-(La \cdot V_p - \text{end}\text{distance} + \text{start}\text{distance})}{V_p}

\text{ProbeOffset} = 0.086

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
Temperature (°C) & Dielectric Permittivity \\
\hline
15 & 82.23 \\
15.5 & 82.04 \\
16 & 81.85 \\
16.5 & 81.67 \\
17 & 81.48 \\
17.5 & 81.29 \\
18 & 81.1 \\
18.5 & 80.92 \\
19 & 80.73 \\
19.5 & 80.55 \\
20 & 80.36 \\
20.5 & 80.18 \\
21 & 79.99 \\
21.5 & 79.81 \\
22 & 79.63 \\
22.5 & 79.44 \\
23 & 79.26 \\
23.5 & 79.08 \\
24 & 78.9 \\
24.5 & 78.72 \\
25 & 78.54 \\
25.5 & 78.36 \\
26 & 78.18 \\
26.5 & 78 \\
\hline
\end{tabular}
\end{table}
### TABLE A-1. Dielectric permittivity values for range of temperatures. From equation [A5].

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Dielectric Permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>27</td>
<td>77.82</td>
</tr>
<tr>
<td>27.5</td>
<td>77.65</td>
</tr>
<tr>
<td>28</td>
<td>77.47</td>
</tr>
<tr>
<td>28.5</td>
<td>77.29</td>
</tr>
<tr>
<td>29</td>
<td>77.12</td>
</tr>
<tr>
<td>29.5</td>
<td>76.94</td>
</tr>
<tr>
<td>30</td>
<td>76.76</td>
</tr>
</tbody>
</table>
Appendix B. Correcting Electrical Conductivity Measurements for System Losses

TDR system cabling and multiplexers introduce losses of the applied and reflected signals which can lead to error in measurement of electrical conductivity. The following information is based on a method presented in paper published by Castiglione and Shouse (2003). The method has been tested by Campbell Scientific and found to provide excellent results. Refinement of the method is provided to allow implementation using Campbell Scientific dataloggers and TDR100 system.

B.1 Description of Method

The method is essentially a calibration and involves collecting system characterization measurements with all system components in place; TDR100, multiplexers, all cabling, and probes. The steps in the process are:

1. measure reflection coefficient with probe rods open and with probe rods shorted
2. determine probe constant, $K_p$, using one solution of known electrical conductivity
3. use values collected in above steps to generate simple function to correct EC measurements
4. incorporate calibration function in datalogger program.

The method defines corrected reflection coefficient, $\rho_{\text{corrected}}$, using the equation

$$\rho_{\text{corrected}} = 2 \left( \frac{\rho_{\text{uncorrected}} - \rho_{\text{open}}}{\rho_{\text{open}} - \rho_{\text{shorted}}} \right) + 1 \quad [B1]$$

$\rho_{\text{corrected}}$ is then used to determine the conductance, $G$, with a TDR probe rods immersed in a solution of known electrical conductivity. $\rho_{\text{uncorrected}}$ is the reflection coefficient at distance 200 m (example given below). The equation for conductance is:

$$G = \left( \frac{1}{Z_u} \right) \left( \frac{1 - \rho_{\text{corrected}}}{1 + \rho_{\text{corrected}}} \right) \quad [B2]$$

with $Z_u$ the system impedance, 50 ohms.

$K_p$ is the slope of a graph of electrical conductivity versus electrical conductance, $\sigma = K_p G$. Since this function passes through the origin, only one measurement of $G$ is needed with a probe immersed in a solution of known conductivity.
Appendix B. Correcting Electrical Conductivity Measurements for System Losses

Electrical conductivity. $K_p$ is calculated as the ratio of electrical conductivity to electrical conductance and presented in equation [B3].

$$K_p = \frac{\sigma}{G} \quad \text{[B3]}$$

With $K_p$ determined, a calibration equation can be derived that corrects EC measurements for system losses.

B.2 Detailed Method Description

B.2.1 Collecting Reflection Coefficient with Probes Open and Shorted

The EC measurement is independent of frequency and uses reflection coefficient values from locations well after probe reflections have stabilized. A distance of 200 meters is chosen for the measurement.

The $\rho_{\text{open}}$ value is collected with the probe suspended in air. The $\rho_{\text{shorted}}$ value is collected with the end of the probe rods shorted while suspended in air. $\rho_{\text{open}}$ and $\rho_{\text{shorted}}$ values are easily determined using PC-TDR. Set waveform parameters to:

Average = 4  Points = 20  Start = 200  Length = 1.

Click Get Waveform and adjust graph scale using the Adjust Axes Range button to allow determination of reflection coefficient to nearest 0.005.

$\rho_{\text{open}}$ and $\rho_{\text{shorted}}$ values can also be collected using a datalogger. See Section B.2.4, CR1000 Program for Collecting $\rho_{\text{open}}$ and $\rho_{\text{shorted}}$ Values, for CR1000 datalogger program that can be used to collect $\rho_{\text{open}}$ and $\rho_{\text{shorted}}$ values.

B.2.2 Determining $K_p$

$K_p$ is the slope of electrical conductivity, $\sigma$, as a function of conductance, $G$. Completely immerse the probe rods in a solution of known or measured electrical conductivity. TABLE B-1 provides KCl amounts for a range of solution electrical conductivities. Since $\sigma$ is zero when $G$ is zero, $K_p$ is simply the ratio of the known or measured electrical conductivity to the conductance, $G$, measured using equations [B3] and [B1].

<table>
<thead>
<tr>
<th>TABLE B-1. Standard KCl Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Conductivity @ 25°C</strong></td>
</tr>
<tr>
<td>(deci siemens/meter)</td>
</tr>
<tr>
<td>111.34</td>
</tr>
<tr>
<td>12.86</td>
</tr>
<tr>
<td>1.409</td>
</tr>
<tr>
<td>0.147</td>
</tr>
</tbody>
</table>
Appendix B. Correcting Electrical Conductivity Measurements for System Losses

The temperature effect is described by:

\[ EC_T = EC_{25} \cdot (1 + 0.02 \cdot (T - 25)) \]  \[ \text{[B4]} \]

where \( EC_{25} \) is the electrical conductivity at 25\(^\circ\)C and \( EC_T \) is the electrical conductivity at other temperatures.

### B.2.3 Deriving Calibration Function

Using the \( K_p \), \( \rho_{\text{open}} \), and \( \rho_{\text{shorted}} \) values for each probe, the uncorrected electrical conductivity as measured by the TDR100 can be corrected to give accurate EC values that account for system losses. To do this, a range of EC values is chosen for \( \sigma_{\text{uncorrected}} \) in equation [B5] and \( \sigma_{\text{corrected}} \) values calculated for the chosen range of \( \sigma_{\text{uncorrected}} \).

\[ \sigma_{\text{corrected}} = -K_p \cdot \frac{\sigma_{\text{uncorrected}} \cdot Z_u - K_p + \rho_{\text{air}} \cdot \sigma_{\text{uncorrected}} \cdot Z_u + \rho_{\text{air}} \cdot K_p}{Z_u \cdot \rho_{\text{shorted}} \cdot \sigma_{\text{uncorrected}} \cdot Z_u + \rho_{\text{shorted}} \cdot K_p + \sigma_{\text{uncorrected}} \cdot Z_u - K_p} \]  \[ \text{[B5]} \]

This equation has a quadratic form. The correction is easier to use if a curve is fit to the \( \sigma_{\text{corrected}} \) values for the chosen range of \( \sigma_{\text{uncorrected}} \). This quadratic is implemented in the datalogger program to give the final result that is corrected electrical conductivity. This must be done for each probe.

![FIGURE B-1. Example of corrected and uncorrected electrical conductivity values.](image)

The fitted equation for this probe is

\[ \sigma_{\text{corrected}} = 0.01 + 0.95 \cdot \sigma_{\text{uncorrected}} + 0.35 \cdot \sigma_{\text{uncorrected}}^2 \]
B.2.4 CR1000 Program for Collecting $\rho_{\text{open}}$ and $\rho_{\text{shorted}}$ Values

'This example program is written for 4 TDR probes connected to a single multiplexer. It will be necessary to add instructions in subroutine TDR if more probes are used.

'CR1000 Series Datalogger
'Declare Public & Dim Variables
Public wave(30), vector(20)
Public rho(2)
Public channel as long
Public Open as boolean
Public Shorted as boolean
Public SDMports as boolean
Public WriteToOutput as boolean
Dim I
'Declare Constants
'Flag logic constants
cost high = true
cost low = false

'Define Data Tables
DataTable (rhoTable,1,-1)
Sample(1,channel,Long)
Sample (2,rho(),IEEE4)
EndTable
'
sub TDR 'set multiplexer address code for specific system
Select Case channel
Case 1
  TDR100 (wave(),0,1,1001,4,1.0,20,200,1.0,0.075,0.0,1,0)
Case 2
  TDR100 (wave(),0,1,2001,4,1.0,20,200,1.0,0.075,0.0,1,0)
Case 3
  TDR100 (wave(),0,1,3001,4,1.0,20,200,1.0,0.075,0.0,1,0)
Case 4
  TDR100 (wave(),0,1,4001,4,1.0,20,200,1.0,0.075,0.0,1,0)
EndSelect
EndSub

'Main Program
BeginProg
Scan (5,sec,0,0)
if Open=high then
  TDR
  For I=1 To 20
    vector(I)=wave(I+9)
  Next
  AvgSpa (rho(1),20,vector(1))
  Open=low
endif

if Shorted=high then
  TDR
  For I=1 To 20
    vector(I)=wave(I+9)
  Next
  AvgSpa (rho(2),20,vector(1))
  Shorted=low
endif
'write results to output storage
If WriteToOutput=high Then
  CallTable rhoTable
  WriteToOutput=low
EndIf
'setting SDMports high will configure control ports 1 thru 3 to allow connection of TDR100 to PC using PC-TDR
If SDMports=high Then
    PortsConfig (&B00000111,&B00000000)
    SDMports=low
EndIf
NextScan
EndProg
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