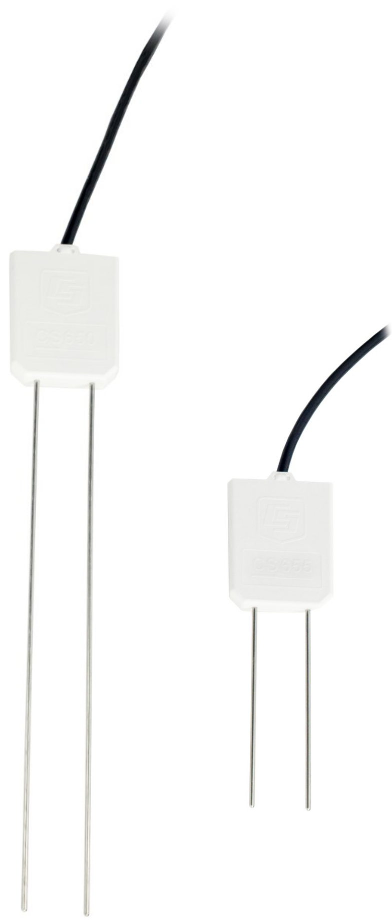
PRODUCT MANUAL

Sensor

CS650 and CS655

Water Content Reflectometers



Revision: 07/2025

RELIABLE MONITORING SINCE 1974

Campbell Scientific®

Please read first

About this manual

Please note that this manual was produced by Campbell Scientific Inc. primarily for the North American market. Some spellings, weights and measures may reflect this. In addition, while most of the information in the manual is correct for all countries, certain information is specific to the North American market and so may not be applicable to European users. Differences include the U.S. standard external power supply details where some information (for example the AC transformer input voltage) will not be applicable for British/European use. Please note, however, *that when a power supply adapter is ordered from Campbell Scientific it will be suitable for use in your country*.

Reference to some radio transmitters, digital cell phones and aerials (antennas) may also not be applicable according to your locality. Some brackets, shields and enclosure options, including wiring, are not sold as standard items in the European market; in some cases alternatives are offered.

Recycling information for countries subject to WEEE regulations 2012/19/EU

At the end of this product's life it should not be put in commercial or domestic refuse but sent for recycling. Any batteries contained within the product or used during the products life should be removed from the product and also be sent to an appropriate recycling facility, per The Waste Electrical and Electronic Equipment (WEEE) Regulations 2012/19/EU. Campbell Scientific can advise on the recycling of the equipment and in some cases arrange collection and the correct disposal of it, although charges may apply for some items or territories. For further support, please contact Campbell Scientific, or your local agent.

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1. Introduction

The CS650 and CS655 are multiparameter smart sensors that use innovative techniques to monitor soil volumetric water content, bulk electrical conductivity, and temperature. The sensors output an SDI-12 signal that many Campbell Scientific data loggers can measure.

The CS650 has 30 cm length rods, whereas the CS655 has 12 cm length rods. This manual uses CS650 to reference model numbers CS650 and CS655. Unless specifically stated otherwise, information in the manual applies equally to both models.

> NOTE:
> This manual provides information only for CRBasic data loggers. For retired Edlog data logger support, see an older manual at www.campbellsci.com/old-manuals.

2. Precautions

- READ AND UNDERSTAND the Safety section at the back of this manual.
- Although the CS650 is rugged, it should be handled as a precision scientific instrument.
- External radio frequency (RF) sources can affect the sensor operation. Therefore, the sensor should be located away from significant sources of RF, such as ac power lines and motors.

3. Initial inspection

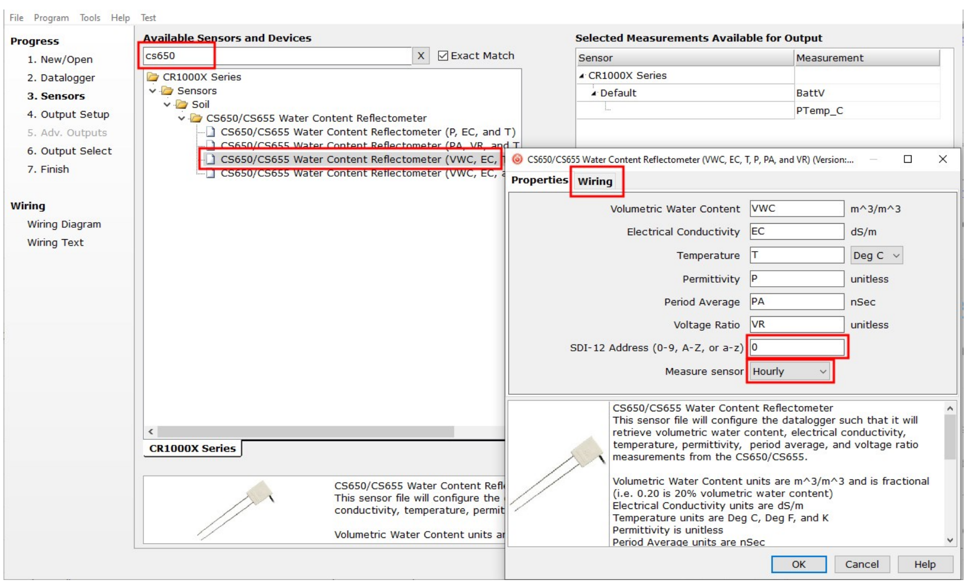
- Upon receipt of the CS650, inspect the packaging and contents for damage. File damage claims with the shipping company.
- The model number and cable length are printed on a label at the connection end of the cable. Check this information against the shipping documents to ensure the expected product and cable length were received.

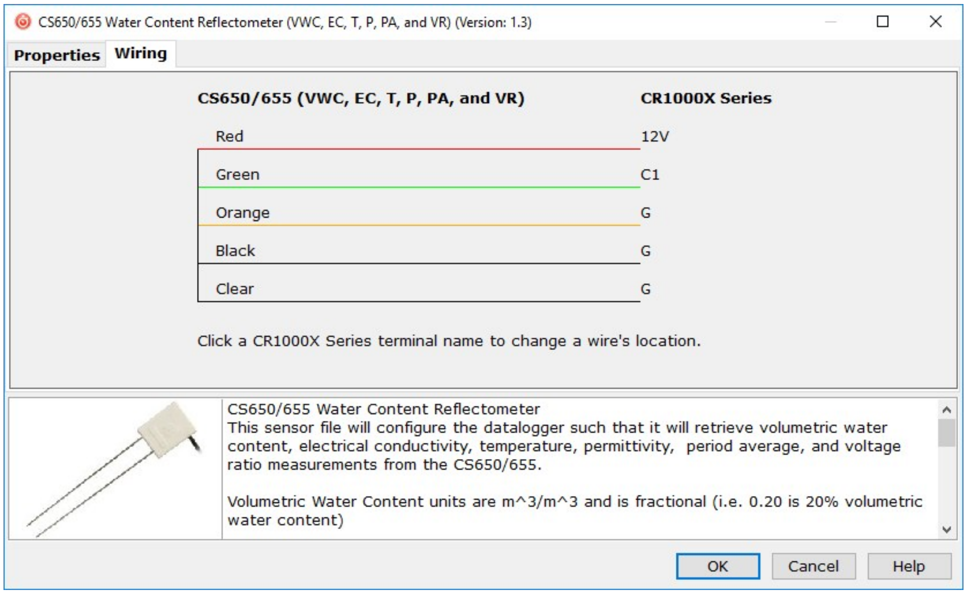
4. QuickStart

A video that describes data logger programming using ***Short Cut*** is available at: www.campbellsci.com/videos/cr1000x-data logger-getting-started-program-part-3. ***Short Cut*** is an easy way to program your data logger to measure the sensor and assign data logger wiring terminals. ***Short Cut*** is available as a download on www.campbellsci.com. It is included in installations of ***LoggerNet***, ***RTDAQ***, and ***PC400***.

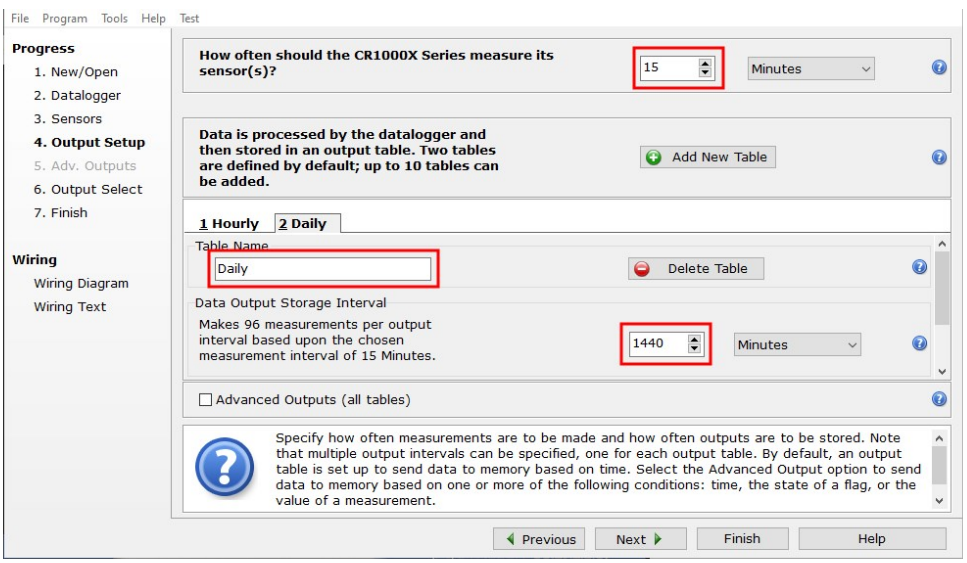
The following procedure also describes programming with Short Cut.

1. Open ***Short Cut*** and click **Create New Program**.
2. Double-click the data logger model.
3. In the **Available Sensors and Devices** box, type CS650. You can also locate the sensor in the **Sensors** > **Meteorological** > **Soil Moisture** > **CS650/CS655 Water Content Reflectometer** folder. The four different options monitor different parameters. For this tutorial, double-click to select **CS650/CS655 Water Content Reflectometer (VWC, EC, T, P, PA, and VR)**. The soil temperature defaults to degree C, and the sensor is measured hourly. These are changed by clicking the **Temperature** or **Measure sensor** box and selecting an option. Enter the correct **SDI-12 Address** for the CS650 or CS655. After entering the **Properties**, click on the **Wiring** tab to see how the sensor is to be wired to the data logger.

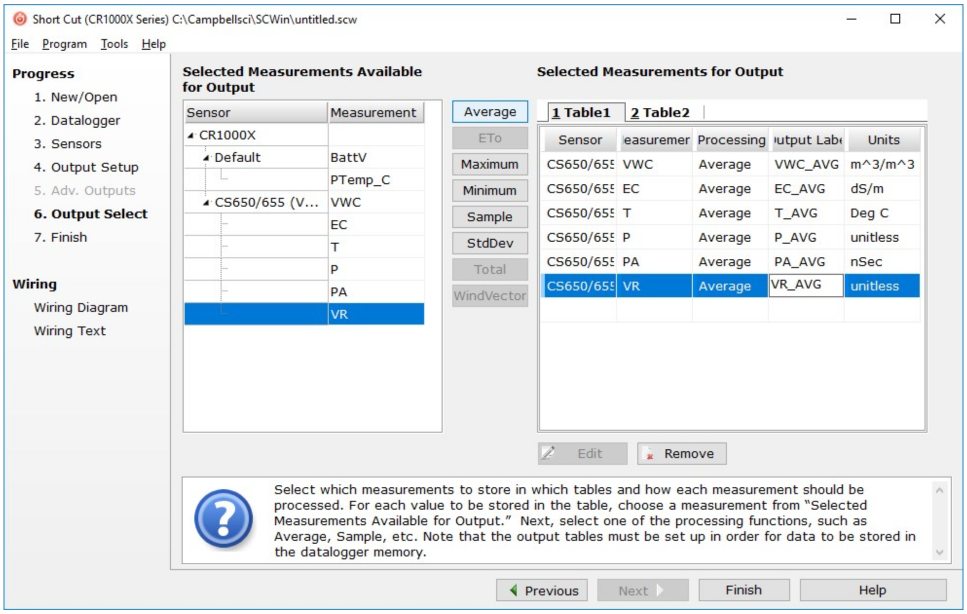




4. Repeat step three for other sensors you want to measure.
5. In **Output Setup**, type the scan rate. If you chose to measure the CS650 hourly rather than every scan, this scan interval must be evenly divisible into an hour. Type a meaningful table name and type the **Data Output Storage Interval**.



6. Select the measurement and its associated output options.



7. Click **Finish** and save the program. Send the program to the data logger if the data logger is connected to the computer.
8. If the sensor is connected to the data logger, check the output of the sensor in the data display in ***LoggerNet***, ***RTDAQ***, or ***PC400*** to make sure it is making reasonable measurements.

5. Overview

The CS650 measures volumetric water content, electrical conductivity, dielectric permittivity, and temperature of soils or other porous media. These values are reported through SDI-12 communications.

Figure 5-1. CS650 (left) and CS655 Water Content Reflectometers

Volumetric water content (VWC) is derived from the sensor sensitivity to the dielectric permittivity of the medium surrounding the sensor stainless-steel rods. The CS650 functions as a water content reflectometer, with the two parallel rods forming an open-ended transmission line. A differential oscillator circuit connected to the rods triggers a state change when it detects a reflected electromagnetic signal. The two-way travel time of the electromagnetic waves that are induced by the oscillator on the rod varies with changing dielectric permittivity. Water is the main contributor to the bulk dielectric permittivity of the soil or porous media, so the travel time of the reflected wave increases with increasing water content and decreases with decreasing water content, hence the name water content reflectometer. The average travel time of the reflected wave multiplied by a scaling factor of 128 is called the period average. Period average is reported in microseconds and is considered to be the raw output of a water content reflectometer.

Electrical conductivity is determined by exciting the rods with a known non-polarizing waveform and measuring the signal attenuation. Signal attenuation is reported as a dimensionless voltage ratio, which is the ratio of the excitation voltage to the measured voltage along the sensor rods when they are excited at a fixed 100 kHz frequency. Voltage ratio ranges from 1 in non-conductive media to about 17 in highly conductive media. Values greater than 17 are highly unstable and indicate the soil conditions are outside of the specified operating range of the sensor.

Temperature is measured with a thermistor in contact with one of the rods.

It is well known that transmission line oscillators used for water content measurements are known to experience unwanted increases in oscillation period due to signal attenuation caused by high electrical conductivity. The CS650 handles this problem by making an electrical conductivity measurement, then correcting the oscillator period accordingly. On-board processing within the sensor head calculates electrical conductivity from the attenuation of the signal, combines this with the oscillator period measurement to determine the dielectric permittivity of the medium, and then applies the Topp equation (Topp et al., 1980) to estimate volumetric water content.

Sensor electronics are encapsulated in the rugged epoxy sensor head.

A five-conductor cable, including the drain or shield wire, provides power, ground, and communications for the CS650. The CS650 is intended to communicate with SDI-12 recorders, including Campbell Scientific data loggers. Alternatively, the orange wire can be used for RS-232 communication. The A200 USB-to-Serial Module allows RS-232 communications between a computer and the CS650 by means of Campbell Scientific's ***Device Configuration Utility*** software.

Features:

- Measurement automatically corrected for soil texture and electrical conductivity effects
- Estimates soil-water content for a wide range of mineral soils
- Versatile sensor—measures dielectric permittivity, bulk electrical conductivity (EC), and soil temperature
- Compatible with Campbell Scientific CRBasic data loggers: CR6 series, CR3000, CR1000X series, CR800 series, CR300 series, and CR1000

6. Specifications

Table 6-1 (p. 6) compares the size of the CS650 and CS655 reflectometers.

Table 6-1: Size specifications

	CS650	CS655
Rods	300 mm long 3.2 mm diameter 32 mm spacing	120 mm long 3.2 mm diameter 32 mm spacing
Sensor head	L 85 mm W 63 mm D 18 mm	L 85 mm W 63 mm D 18 mm
Sensor weight	280 g	240 g
Cable weight	35 g/m	35 g/m

Ingress protection rating: IP68

Compliance information: View at: www.campbellsci.com/cs650
www.campbellsci.com/cs655

6.1 Electrical specifications

Sensor output:	SDI-12 Serial RS-232
Warmup time:	3 s
Measurement time:	3 ms to measure 600 ms to complete SDI-12 command
Power supply requirements:	6 to 18 VDC Must be able to supply 45 mA @ 12 VDC
Maximum cable length:	610 m (2000 ft) combined length for up to 25 sensors connected to the same data logger control or U terminal[1]
Electromagnetic:	External radio frequency (RF) sources can affect CS650 measurements. CS650 circuitry should be located away from radio transmitter aerials and cables or measurements should be discarded during RF transmissions.
Active current drain (3 ms):	45 mA typical @ 12 VDC (80 mA @ 6 VDC, 35 mA @ 18 VDC)
Quiescent current drain:	135 µA @ 12 VDC
Average current drain:	I = 0.09n + [3.5 + 0.024(n-1)]n/s I = average current in milliamps n = number of CS650s s = number of seconds between measurements (see Figure 6-1 [p. 8])

[1]Campbell Scientific recommends using separate terminals when possible.

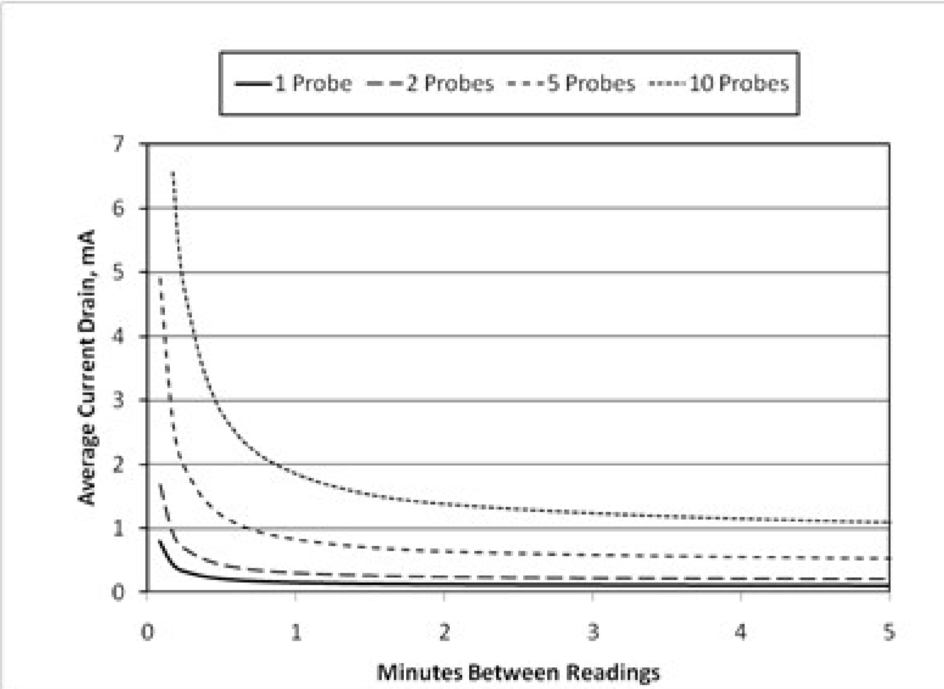


Figure 6-1. CS650 and CS655 average current drain

Figure 6-1 (p. 8) shows average current drain for different measurement rates and quantities of CS650 sensors. If the time between measurements is five minutes or longer, average current drain is approximately 0.15 milliamps per sensor.

6.2 Operational specifications

Table 6-2 (p. 8) provides the operational specifications.

Table 6-2: Relative dielectric permittivity specifications		
	CS650	CS655
Relative dielectric permittivity		
Range	1 to 81	
Accuracy† 1 to 40: 40 to 80:	±(2% of reading + 0.6) for solution electrical conductivity (EC) ≤3 dS/m ±1.4 for solution EC ≤3 dS/m	±(3% of reading + 0.8) for solution EC ≤8 dS/m ±2 for solution EC ≤2.8 dS/m
Precision‡	<0.02	

Table 6-2: Relative dielectric permittivity specifications		
	CS650	CS655
Volumetric water content		
Range	0% to 100%	
Accuracy†	±1% (with soil specific calibration), ±3% (typical with factory VWC model) where solution EC < 3 dS/m	±1% (with soil specific calibration), ±3% (typical with factory VWC model) where solution EC < 10 dS/m
Precision‡	<0.05%	
Electrical conductivity		
Range solution EC	0 to 3 dS/m	0 to 8 dS/m
Range bulk EC	0 to 3 dS/m	0 to 8 dS/m
Accuracy†	±(5% of reading + 0.05 dS/m)	
Precision‡	0.5% of bulk electrical conductivity (BEC)	
Temperature		
Range	–50 to 70 °C	
Resolution	0.001 °C	
Accuracy†	±0.1 °C (for typical soil temperatures [0 to 40 °C] when sensor body is buried in soil), ±0.5 °C for full temperature range	
Precision‡	±0.02 °C	
Sensing volume*	7800 cm^3	3600 cm^3

***Sensing volume** approximately 7.5 cm radius around each sensor rod and 4.5 cm beyond the end of the rods

†**Accuracy** specifications are based on laboratory measurements in a series of solutions with dielectric permittivities ranging from 1 to 81 and solution electrical conductivities ranging from 0 to 3 dS/m.

‡**Precision** describes the repeatability of a measurement. It is determined for the CS650 by taking repeated measurements in the same material. The precision of the CS650 is better than 0.05 % volumetric water content and 0.01 dS/m electrical conductivity.

7. Installation

Watch the video, Installing a Soil Moisture Reflectometer Sensor ▶, to see a demonstration of proper installation of a CS650 or CS655 sensor.

If you are programming your data logger with ***Short Cut***, skip Data logger wiring (p. 11) and Programming (p. 12). ***Short Cut*** does this work for you. See QuickStart (p. 2) for a ***Short Cut*** tutorial.

7.1 Orientation and placement

The CS650 measures the bulk dielectric permittivity, average volumetric water content, and bulk electrical conductivity (EC) along the length of the rods, which is 30 cm for the CS650 and 12 cm for the CS655. The sensor rods can insert vertically into the soil surface or be buried at any orientation to the surface. Install the sensor horizontal to the surface to detect the passing of wetting fronts or other vertical water fluxes.

The sensitive volume depends on the surrounding media. In soil, the sensitive volume extends approximately 7.5 cm (3 in) from the rods along their length and 4.5 cm (1.8 in) beyond the end of the rods. Consequently, if the sensor is buried horizontally closer than 7.5 cm from the soil surface, it includes air above the surface in its measurements and underestimates soil water content.

The thermistor used to measure temperature is in contact with one of the stainless steel rods at the base of the epoxy sensor body. Because of the low thermal conductivity of stainless steel, the thermistor does not measure the average temperature along the rod, but instead provides a point measurement of the temperature within the epoxy. For a valid soil temperature reading, the sensor body must be in thermal equilibrium with the soil. Also, bury the sensor head in the soil so that it is insulated from diurnal temperature fluctuations.

7.2 Proper insertion

The method used for sensor installation affects the accuracy of the measurement. Insert the sensor rods as close to parallel as possible. The sensor is more sensitive to permittivity close to the rods. Air voids around the rods result in reduced measurement accuracy. Most soils recover from disturbances caused by installation.

The CS650G Rod Insertion Guide Tool with Pilot Rod helps maintain the proper spacing and parallel orientation of the rods during sensor insertion. It also helps the insertion of the sensor in high density or rocky soils.

Figure 7-1. CS650G Rod Insertion Guide Tool with Pilot Rod

7.3 Data logger wiring

Campbell Scientific data loggers typically use SDI-12 to measure the sensor because RS-232 communications require more terminals per CS650, and RS-232 programming is more complicated than SDI-12 programming.

Table 7-1 (p. 12) shows the SDI-12 wiring for the CS650 water content reflectometer. SDI-12 data is transmitted to a CRBasic data logger odd numbered control or U terminal. Wiring information for RS-232 communications is provided in A200 and Device Configuration Utility (p. 13).

Table 7-1: Wire color, function, and data logger connection for SDI-12

Color	Function	Data logger connection
Green	SDI-12 data	**C**, SDI-12, or **U** configured for SDI-12[1]
Red	SDI-12 power	**12V**
Black	SDI-12 reference	**G**
Clear	Shield	**G**
Orange	Not used	**G**

[1]**U** terminals are automatically configured by the measurement instruction.

> NOTE:
> The orange wire is only used for RS-232 communications and should be grounded when using SDI-12.

For the CR6 and CR1000X data loggers, triggering conflicts may occur when a companion terminal is used for a triggering instruction, such as `TimerInput()`, `PulseCount()`, or `WaitDigTrig()`. For example, if the CS650 is connected to C3 on a CR1000X, C4 cannot be used in the `TimerInput()`, `PulseCount()`, or `WaitDigTrig()` instructions.

7.4 Programming

Short Cut is the best source for up-to-date programming code for Campbell Scientific data loggers. If your data acquisition requirements are simple, you can probably create and maintain a data logger program exclusively with ***Short Cut***. If your data acquisition needs are more complex, the files that ***Short Cut*** creates are a great source for programming code to start a new program or add to an existing custom program.

> NOTE:
> ***Short Cut*** cannot edit programs after they are imported and edited in ***CRBasic Editor***.

A ***Short Cut*** tutorial is available in QuickStart (p. 2). If you wish to import ***Short Cut*** code into ***CRBasic Editor*** to create or add to a customized program, follow the procedure in Importing Short Cut code into CRBasic Editor (p. 35). Programming basics for CRBasic data loggers are provided in this section. Complete program examples for select CRBasic data loggers can be found in Example programs (p. 36).

Use the `SDI12Recorder()` instruction to measure the sensor. This instruction sends a request to the sensor to make a measurement and retrieves the measurement values from the sensor. See SDI-12 measurements (p. 19) for more information.

For most CRBasic data loggers, the `SDI12Recorder()` instruction has the following syntax:

```
SDI12Recorder(Destination, SDIPort, SDIAddress, "SDICommand", Multiplier, Offset,
FillNAN, WaitonTimeout)
```

The `Destination` parameter must be an array. The required number of values in the array depends on the command (Table 8-3 [p. 19]).

`FillNAN` and `WaitonTimeout` are optional parameters (refer to CRBasic Help for more information).

8. Operation

8.1 A200 and *Device Configuration Utility*

The A200 Sensor-to-Computer Interface allows communications between a CS650 and a computer to change sensor settings through ***Device Configuration Utility*** software. ***Device Configuration Utility*** is included in installations of ***LoggerNet***, ***RTDAQ***, and ***PC400***. It can also be downloaded separately using this link: www.campbellsci.com/devconfig.

If the A200 has not been previously plugged into your computer and your computer operating system is not Windows 7 or above, the A200 driver needs to be installed.

> **NOTE:**
> Drivers should be installed before plugging the A200 into the computer.

To download the A200 drivers, go to www.campbellsci.com/downloads/a200-sensor-interface-usb-driver and click **Download Now**.

One end of the A200 has a terminal block, while the other end has a type B female USB port. The terminal block provides **12V**, **G**, **Tx**, and **Rx** terminals for connecting the sensor (see Figure 8-1 [p. 14] and Table 8-1 [p. 14]).

Figure 8-1. A200 Sensor-to-Computer Interface

A data cable that ships with the A200 has a USB type-A male connector for attaching to a computer USB port and a type B male connector for attaching to the A200 USB port.

Table 8-1: CS650 wiring code for RS-232 and A200

Color	Function	A200 terminal
Orange	RxD	**Rx**
Green	TxD	**Tx**
Red	Power	**+12 VDC**
Black	Reference	**G**
Clear	Shield	**G**

The A200 provides power to the sensor when it is connected to a computer USB port. An internal DC/DC converter boosts the 5 VDC supply from the USB connection to a 12 VDC output that is required to power the sensor.

8.1.1 Determining which COM port the A200 has been assigned

When the A200 driver is installed, the A200 is assigned a COM port number. This COM port number is needed when using ***Device Configuration Utility***. Often, the assigned COM port is the next port number that is free. However, if other devices were previously installed (some of which may not be plugged in), the A200 may be assigned a higher COM port number.

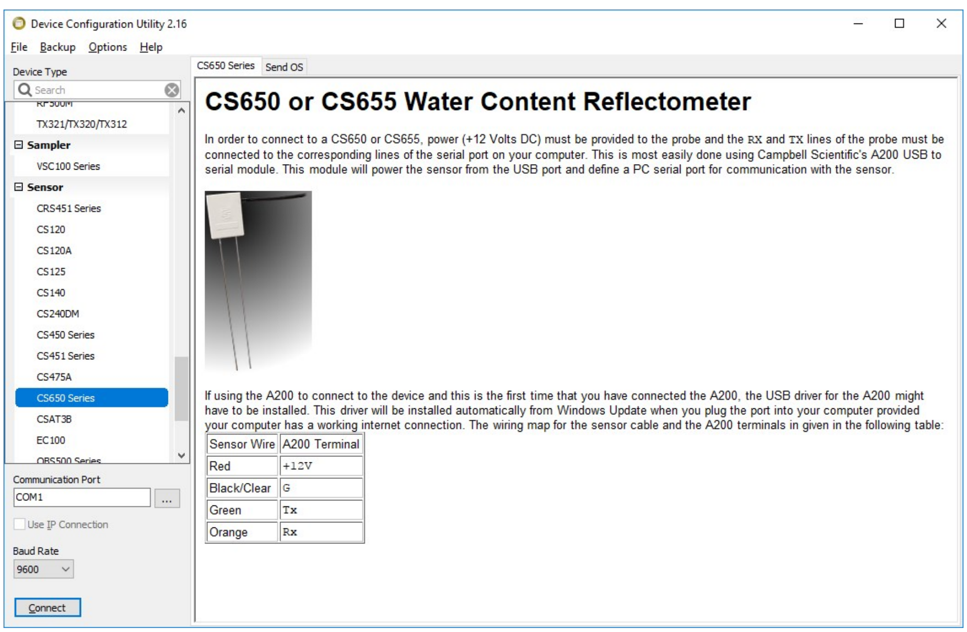
To check which COM port has been assigned to the A200, monitor the appearance of a new COM port in the list of COM ports offered in your software package, such as ***LoggerNet***, before and after the installation, or look in the Windows Device Manager list under the ports section (access via the control panel).

8.1.2 *Device Configuration Utility*

The ***Device Configuration Utility*** is available as a download on www.campbellsci.com/downloads. It is included in installations of ***LoggerNet***, ***RTDAQ***, or ***PC400***.

Connect the CS650 to the A200 as shown in Figure 8-1 (p. 14). Connect the computer to the A200 USB port with the supplied USB cable.

Launch ***Device Configuration Utility*** and search for **CS650 Series** from the **Device Type** list on the left. Select 9600 from the **Baud Rate** list.

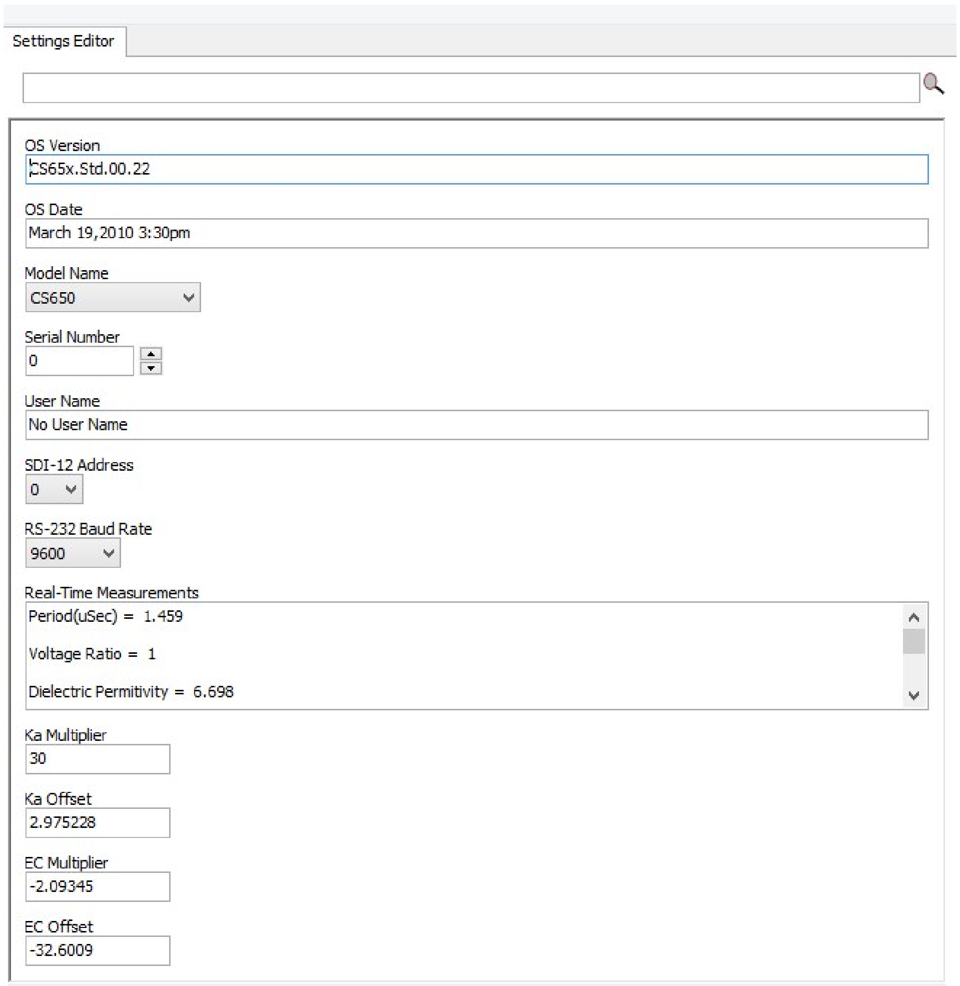


Browse for and select the Communications Port used for your device (see Determining which COM port the A200 has been assigned [p. 15]).

Select **Ok** then **Connect** to begin communications with the CS650.

8.1.2.1 Settings Editor tab

The **Settings Editor** tab shows settings stored in the CS650 operating system. Settings that may be modified include **User Name**, **SDI-12 Address**, and **RS-232 Baud Rate**. Attempts to change any of the other settings results in a "Commit failed. Unrecognized error condition" error message. ***Device Configuration Utility*** polls the CS650 every two seconds while connected and the results are displayed under **Real-Time Measurements** (Table 8-2 [p. 18]). This is useful for verifying sensor performance.



Default communications settings are 9600 baud, no parity, 1 stop bit, 8 data bits, and no error checking. After any changes to CS650 settings, select **Apply** to write the changes to the CS650 operating system. A configuration summary is then shown. The summary may be printed or saved electronically for future reference.

Current Device Settings Summary

Configuration of CS650 Series

Configured on: Monday, February 26, 2018 3:22:57 PM

Setting Name	Setting Value
	CS65x.Std.00.22
	March 19,2010 3:30pm
Model_Name	CS650
Sensor SN	4,294,967,295
	No User Name
SDI-12_Address	0
Baud_Rate	9600
Real-Time Measurements	**Measurement Field Name** / **Measurements** Period(uSec) = 1.459 Voltage Ratio = 1 Dielectric Permitivity = 6.698 Volumetric Water Content = 0.1192 Electrical Conductivity(dS/m) = 0.0204 Temperature(°C) = 26.16
Ka_Mult	30

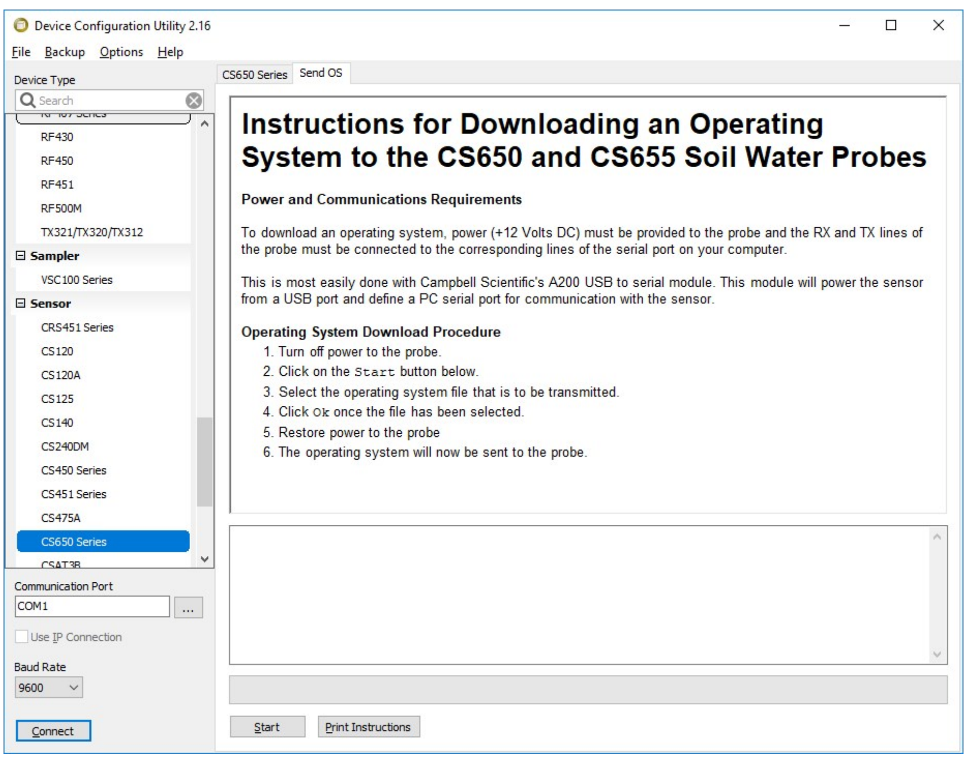
Ok Save Print Compare

Table 8-2: Real-Time Measurements	
Measurement field name	**Meaning**
VWC	Volumetric water content
EC (dS/m)	Bulk electrical conductivity
TS (°C)	Soil temperature
Ka	Bulk dielectric permittivity
PA (µS)	Period average
VR	Voltage ratio

8.1.2.2 Send OS tab

The **Send OS** tab is used to update the operating system in the CS650. The operating system is available at www.campbellsci.com/downloads. The file to send has a filename extension of *.a43*, such as *CS65X.Std.02.a43*. Sending a new operating system does not affect any of the user-modified settings or sensor specific multiplier and offset settings.

To download a new operating system, follow the **Operating System Download Procedure** listed on the **Send OS** tab.



8.2 SDI-12 measurements

The CS650 responds to SDI-12 commands `M!`, `M1!`, `M2!`, `M3!`, `M4!`, `?!`, and `I!`. Table 8-3 (p. 19) shows the values returned for each of these commands.

Establish SDI-12 communications using the `SDI12Recorder()` CRBasic instruction. See Data logger wiring (p. 11) for SDI-12 wiring details.

NOTE:
This section briefly describes using SDI-12 commands. Additional SDI-12 information is available at SDI-12 sensor support (p. 41), www.sdi-12.org, or www.youtube.com/user/CampbellScientific.

Table 8-3: CS650 SDI-12 commands

SDI-12 command ("a" is the sensor address)	Values returned	Units
`aM!`	1. Volumetric Water Content, q 2. Electrical Conductivity, s 3. Temperature	m^3/m^3 dS/m °C
`aM1!`	1. Permittivity, e 2. Electrical Conductivity, s 3. Temperature	 dS/m °C
`aM2!`	1. Period, t 2. Voltage Ratio, a 3. Temperature	µs °C
`aM3!`	1. Volumetric Water Content, q 2. Electrical Conductivity, s 3. Temperature 4. Permittivity, e 5. Period, t 6. Voltage Ratio, a	m^3/m^3 dS/m °C µs

Table 8-3: CS650 SDI-12 commands		
SDI-12 command ("a" is the sensor address)	Values returned	Units
aM4!	1. Volumetric Water Content, q 2. Electrical Conductivity, s 3. Temperature 4. Permittivity, e 5. Period, t 6. Voltage Ratio, a	m^3/m^3 dS/m °C µs
aM5! .. aM9!	No Values Returned	
?!	Returns the SDI-12 Address	
aI!	CampbellSci, Operating System Version, Product Serial Number	

Campbell Scientific recommends using separate terminals when possible. However, multiple CS650 sensors can connect to the same data logger control or **U** terminal. Each must have a unique SDI-12 address. Valid addresses are 0 through 9, A through Z, and a through z. The CS650 ships with a default SDI-12 address of 0 unless otherwise specified at the time of ordering. Change the SDI-12 address through ***Device Configuration Utility*** (see A200 and Device Configuration Utility [p. 13]) or with a terminal emulator in SDI-12 transparent mode (see SDI-12 sensor support [p. 41]).

8.3 M3! and M4! commands

Typically, the M4! command is used to report volumetric water content, electrical conductivity, temperature, permittivity, period, and voltage ratio. The M4! command reports the sensor calculated values, even if those values are likely to be erroneous.

The M3! command uses several logical tests built into the operating system to ensure the sensors do not report a number that is likely to be erroneous. Erroneous readings are either outside the sensor operational limits or outside of published accuracy specifications. When one of the following conditions occurs, the logical test replaces the calculated value with another value such as 9999999 or NAN.

Permittivity < 0 or > 88

The equation used to convert period average and electrical conductivity values to permittivity is a three-dimensional surface with two independent variables and eleven coefficients, plus an offset.

Combinations of period and electrical conductivity result in a permittivity calculation that is less than zero or greater than 88. These rare combinations are not expected when the sensor is in soil, but if they do occur, the `M3!` command reports NAN for permittivity.

Permittivity < 1

If the CS650 calculates a permittivity value greater than zero but less than 1, the `M3!` command reports a permittivity value of 1.

Permittivity too low for the Topp et al equation

The Topp et al (1980) equation used by the CS650 to estimate volumetric water content works well for most mineral soils. However, at low water contents, the Topp equation may report a negative value for volumetric water content. When the estimated permittivity is greater than 1 but less than 1.881, the `M3!` command reports a volumetric water content value of zero.

Permittivity more than 42

The Topp et al (1980) equation used by the CS650 to estimate volumetric water content works well for most mineral soils up to a maximum water content of about 0.45. If the CS650 estimates the soil permittivity to be more than 42, which calculates to a volumetric water content of 0.52, then the `M3!` command reports 9999999 or NAN for volumetric water content.

Calculated permittivity is less than 80% of the permittivity limit

A permittivity limit based on the bulk electrical conductivity (EC) reading is used to determine whether the bulk EC at saturation exceeds the sensor operational limit. That permittivity limit is calculated and compared to the permittivity reading. If the measured permittivity is more than 20% beyond the permittivity limit, the `M3!` command reports NAN or 9999999 for both permittivity and volumetric water content. This is the most common cause of NAN values with the CS650-series sensors, and it occurs because of soil properties and not because of a sensor malfunction.

Bulk electrical conductivity (EC) is too high

When bulk electrical conductivity is greater than 1.14 dS/m, the solution EC is greater than 3 dS/m, which is the upper limit for accurate readings with the CS650. For the CS655, the upper limit for bulk EC is 3.04 dS/m, corresponding to a solution EC of 8 dS/m. When this bulk EC condition occurs, the soil is considered out-of-bounds and the `M3!` command reports NAN or 9999999 for both permittivity and volumetric water content.

Voltage ratio is too high

When the voltage ratio is greater than 17, bulk electrical conductivity readings become unstable. When this bulk EC condition occurs, the `M3!` command reports NAN or 9999999 for both permittivity, volumetric water content, and bulk EC.

8.4 Use of multiplexers

Multiplexers such as Campbell Scientific AM16/32B can connect up to 32 CS650 sensors to a single control or **U** terminal. When using multiplexers, the simplest configuration is for all sensors to have the same SDI-12 address.

When multiplexing CS650 sensors, use the switched 12V terminal so power to the sensor is turned off under program control before the multiplexer switches to the next terminal.

> CAUTION:
> Failure to turn off the switched 12 Volt terminal before clocking the multiplexer damages the multiplexer relays.

The proper sequence in the data logger program for measuring CS650 sensors on a multiplexer is:

1. Set RES control port high to enable multiplexer
2. Pulse CLK control port to advance to next multiplexer terminal
3. Set switched 12 volt terminal high to supply power to CS650
4. Delay for 3 seconds for sensor to warm up
5. Send SDI-12 command(s) to CS650
6. Set switched 12 volt terminal low to remove power from CS650
7. Repeat steps 2 through 5 for each CS650 connected to the multiplexer
8. Set RES control port low to disable multiplexer

Program examples in Example programs (p. 36) show the commands used in CRBasic.

For video tutorials on using multiplexers with Campbell Scientific data loggers, see:

www.campbellsci.com/videos/wiring-a-datalogger-to-a-multiplexer

www.campbellsci.com/videos/multiplexer-programming-with-a-cr1000-datalogger

8.5 Water content reflectometer method for measuring volumetric water content

For the water content measurement, a differential emitter-coupled logic (ECL) oscillator on the circuit board is connected to the two parallel stainless steel rods. The differentially driven rods form an open-ended transmission line in which the wave propagation velocity is dependent upon the dielectric permittivity of the media surrounding the rods. An ECL oscillator state change is triggered by the return of a reflected signal from the end of one of the rods.

The fundamental principle for CS650 water content measurement is the velocity of electromagnetic wave propagation along the sensor rods is dependent on the dielectric permittivity of the material surrounding the rods. As water content increases, the propagation velocity decreases because of increasing dielectric permittivity. Therefore, the two-way travel time of the rod signal is dependent upon water content, hence the name water content reflectometer. Digital circuitry scales the high-speed oscillator output to an appropriate frequency for measurement by an onboard microprocessor. Increases in oscillation period resulting from signal attenuation are corrected using an electrical conductivity measurement. A calibration equation converts period and electrical conductivity to bulk dielectric permittivity. The Topp equation is used to convert from permittivity to volumetric water content.

8.5.1 Topp equation

The relationship between dielectric permittivity and volumetric water content in mineral soils has been described by Topp et al. (1980) in an empirical fashion using a third-degree polynomial. With θ_v the volumetric water content and K_a the bulk dielectric permittivity of the soil, the equation presented by Topp et al. is

$$\theta_v = -5.3 \cdot 10^{-2} + 2.92 \cdot 10^{-2} K_a - 5.5 \cdot 10^{-4} K_a^2 + 4.3 \cdot 10^{-6} K_a^3$$

Research has shown this equation works well in most mineral soils, so a soil specific calibration of the CS650 sensor is usually not necessary. For a soil specific calibration, you can generate an equation relating K_a to θ_v following the methods described in Water content reflectometer user-calibration (p. 26).

8.5.2 Soil electrical conductivity

The quality of soil water measurements which apply electromagnetic fields to wave guides is affected by soil electrical conductivity. The propagation of electromagnetic fields in the configuration of the CS650 is predominantly affected by changing dielectric permittivity due to changing water content, but it is also affected by electrical conductivity. Free ions in soil solution provide electrical conduction paths, which result in attenuation of the signal applied to the waveguides. This attenuation both reduces the amplitude of the high-frequency signal on the sensor rods and reduces the bandwidth. The attenuation reduces oscillation frequency at a given water content because it takes a longer time to reach the oscillator trip threshold.

It is important to distinguish between soil bulk electrical conductivity and soil solution electrical conductivity. Soil solution electrical conductivity refers to the conductivity of the solution phase of soil. In the laboratory, extraction methods can determine soil solution electrical conductivity,

$\sigma_{solution}$. These extraction methods separate the solution from the solid, then measures the electrical conductivity of the extracted solution.

The following describes the relationship between solution and bulk electrical conductivity (Rhoades et al., 1976)

$$\sigma_{bulk} = \sigma_{solution}\theta_v T + \sigma_{solid}$$

where σ_{bulk} is the electrical conductivity of the bulk soil; $\sigma_{solution}$, the soil solution; σ_{solid}, the solid constituents; θ_v, the volumetric water content; and T, a soil-specific transmission coefficient intended to account for the tortuosity of the flow path as water content changes. See Rhoades et al., 1989 for a form of this equation which accounts for mobile and immobile water. This publication also discusses soil properties related to CS650 operation, such as clay content and compaction. The above equation is presented here to show the relationship between soil solution electrical conductivity and soil bulk electrical conductivity.

Most expressions of soil electrical conductivity are given in terms of solution conductivity or electrical conductivity from extract since it is constant for a soil. Bulk electrical conductivity increases with water content, so comparison of the electrical conductivity of different soils must be at the same water content.

The calibration equation in the CS650 operating system corrects the oscillation frequency for the effects of $\sigma_{solution}$ up to 3 dS/m for the CS650 and up to 10 dS/m for the CS655. This is equivalent to σ_{bulk} values of approximately 0.8 dS/m and 2.7 dS/m respectively. If σ_{bulk} exceeds these limits, the CS650 sensor returns 99999 for dielectric permittivity and volumetric water content. The measured period average and voltage ratio values continue to report even if the bulk EC is outside the operational range of the sensor.

8.5.3 Temperature correction of soil electrical conductivity

The EC value reported by the CS650 is bulk electrical conductivity. This value is temperature dependent, changing by 2% per degree Celsius. To compensate for the effect of temperature, convert EC readings to a standard temperature, such as 25 °C using the following equation:

$$EC_{25} = EC_T / (1 + 0.02 \bullet (T_{soil} - 25))$$

where EC_{25} is the σ_{bulk} value at 25 °C and ECT is the σ_{bulk} value at soil temperature T_{soil} (°C).

8.5.4 Error sources in water content reflectometer measurement

All manufactured CS650s/CS655s are checked in standard media to develop a sensor specific span and offset value for electrical conductivity and dielectric permittivity measurements. These sensor specific values are written to the sensor operating system and minimize sensor-to-sensor variability.

The method used for sensor insertion can affect the accuracy of the measurement. The sensor rods should be kept as close to parallel as possible when inserted to maintain the design wave guide geometry. The sensitivity of this measurement is greater in the regions closest to the rod surface than at distances away from the surface. Sensors inserted in a manner that generates air voids around the rods indicate lower water content than actual. In some applications, the CS650G insertion and pilot tool helps maintain the proper spacing and parallel orientation of the rods during sensor insertion.

8.5.5 Temperature dependence and correction

The two temperature dependent sources of error in CS650 water content measurements are the effect of temperature on the operation of the sensor electronics and the effect of temperature on the dielectric permittivity of the soil.

The effect of temperature on sensor electronics is minimal with period average readings varying by less than 0.5% of the 20 °C reading over the range of 10 to 30 °C and less than 2% of the 20 °C reading over the range of –10 to 70 °C.

The larger error is caused by the change in dielectric permittivity of soil with temperature. This is mostly due to the high temperature dependence of the permittivity of water, which varies from a value of 88 at 0 °C to 64 at 70 °C. Since water is the major contributor to bulk dielectric permittivity of soil, temperature related changes to the permittivity of water lead to overestimation of volumetric water content at temperatures below 20 °C and underestimation of volumetric water content at temperatures above 20 °C.

The Topp equation does not account for soil temperature. The effect of temperature on the soil permittivity is related to soil specific properties, such as porosity and the permittivity of the soil solid phase with temperature. Consequently, a general equation that corrects volumetric water content for temperature for all soils is not available.

A temperature correction equation that works well in quartz sand is given by:

$$\theta_{Corr} = \theta - 0.0044 \cdot T\theta^3 + 0.0014 \cdot T\theta^2 + 0.0029 \cdot T\theta - 0.0002 \cdot T + 2.4 \cdot \theta^3 - 1.6 \cdot \theta^2 + 0.32 \cdot \theta - 0.046$$

where θ_{Corr} is the temperature corrected volumetric water content, T is soil temperature in °C, and θ is the volumetric water content value at soil temperature T.

The thermistor used for measuring soil temperature is located in the sensor head and is in contact with one of the stainless steel rods. To make an accurate soil temperature measurement, the sensor head should be buried in the soil so it is insulated from diurnal temperature fluctuations.

8.6 Water content reflectometer user-calibration

While the Topp equation works well in a wide range of mineral soils, there are soils for which a user-derived calibration optimizes accuracy of the volumetric water content measurement. The Topp equation underestimates the water content of some organic, volcanic, and fine textured soils. Additionally, porous media with porosity greater than 0.5 or bulk density greater than 1.55 g cm^{-3} may require a media-specific calibration equation.

In these cases, the user may develop a calibration equation to convert CS650 permittivity to volumetric water content over the range of water contents the sensor is expected to measure.

8.6.1 User-derived calibration equation

A quadratic equation or third order polynomial can describe the relationship between soil permittivity and volumetric water content. In many applications, a linear equation similar to Ledieu et al (1986) gives required accuracy.

Quadratic form:

$$\theta_v(K_a) = C_0 + C_1 \bullet K_a + C_2 \bullet K_a^2$$

with θ_v the volumetric water content, K_a the bulk dielectric permittivity of the soil, and Cn, the calibration coefficient.

Third-degree polynomial form:

$$\theta_v(K_a) = C_0 + C_1 \bullet K_a + C_2 \bullet K_a^2 + C_3 \bullet K_a^3$$

with θ_v the volumetric water content, K_a the bulk dielectric permittivity of the soil, and Cn, the calibration coefficient.

Linear form:

$$\theta_v(K_a) = C_0 + C_1 \bullet K_a^{0.5}$$

with θ_v the volumetric water content, K_a the bulk dielectric permittivity of the soil, and Cn, the calibration coefficient.

Two data points from careful measurements sometimes are enough to derive a linear calibration. Use at least three data points for a quadratic calibration. With three evenly spaced water contents covering the expected range, the middle water content data point indicates whether a linear or polynomial calibration equation is needed.

Use at least four data points for the derivation of a third-degree polynomial. Space the data points as evenly as practical over the expected range of water content and include the wettest and driest expected values.

8.6.2 Collecting laboratory data for calibration

Water content reflectometer data needed for CS650 calibration are the CS650 permittivity reading and an independently determined volumetric water content. From this data, a linear or polynomial function can describe the sensor response to changing water content. For more information, refer to User-derived calibration equation (p. 26).

Required equipment:

- CS650 connected to data logger programmed to measure permittivity.
- Cylindrical sampling devices to determine sample volume for bulk density, such as copper tubing with diameter of ≥ 1 inch and length at about 2 inches.
- Non-metal container, such as a PVC pipe (20 cm diameter, 35 cm length) with one end closed. The container should be large enough to ensure only soil is within 10 cm (4 in) of the CS650 rod surface.
- Oven or microwave safe container of known weight.
- Scale to measure soil sample mass.
- Oven or microwave to dry samples.

The calibration coefficients are derived from a curve fit of known water content and sensor permittivity output. The number of data sets needed to derive a calibration depends on the form of the calibration equation. At least three data sets should be generated to determine whether the linear form is valid. If a polynomial is to be used, four data sets determine whether the function is a quadratic or third order polynomial. Accuracy requirements may need additional data sets. Consider the expected range of soil water content and include data sets from the highest and lowest expected water contents.

Calibration procedure:

1. Use relatively dry soil (volumetric water content <10%), which ensures the soil is homogeneous around the sensor rods.

2. Uniformly pack the non-metal container with soil. Compaction of the calibration soil needs to have similar bulk density as the soil at the field site. Follow this method to ensure the soil is compacted uniformly:
    a. Roughly separate the soil into three or more equal portions.
    b. Evenly place a loose soil layer in the bottom of the container.
    c. Tamp the soil to a level that is correct for the target bulk density. Dry soil without compaction has a typical bulk density, 1.1 to 1.4 g cm^{-3}. This step is especially important when bulk density is greater than 1.55 g cm^{-3}.
    d. Scarify (loosen) the top of the compacted layer.
    e. Repeat steps b through d for each of the remaining soil layers.
3. Carefully insert CS650 rods through the soil surface until the rods are completely surrounded by soil. Avoid moving the rods from side to side because this can form air voids around the rods.
4. Collect the sensor permittivity output and remove sensor.
5. Repeat steps 3 and 4 three or four times.
6. Add water to top of the container.
7. Cover the container to prevent evaporation.
8. Frequently observe the CS650 permittivity output, waiting for the permittivity to be constant. This indicates equilibration. The time required for equilibration depends on the amount of water added and the hydraulic properties of the soil.
9. Record the CS650 permittivity.
10. Repeat steps 6 through 9.
11. Remove the CS650.
12. Take core samples of soil using this process:
    a. Evenly push copper tubing into the soil where the sensor rods were inserted.
    b. Remove the tube containing the sample and gently trim the ends of excess soil.
    c. Remove excess soil from outside of the tube.
    d. Transfer the soil from the tube to the oven or microwave safe container.
    e. Weigh the container holding the wet soil and subtract the container weight from this value to get the wet soil mass.
    f. Record the wet soil mass.

g. Use oven or microwave to remove water from soil. Oven drying requires 24 hours at 105 °C. Microwave drying typically takes 20 minutes depending on microwave power and sample water content. ASTM Method D4643-93 requires heating in microwave for 3 minutes, cooling in desiccator, then weighing and repeating this process until measured mass is constant (References [p. 34]).

h. Weigh the container holding the dry soil and subtract the container weight from this value to get the dry soil mass.

i. Record the dry soil mass.

j. Repeat process to take replicate samples. Three carefully handled samples provide good results.

13. Calculate gravimetric water content from wet mass of sample (m_{wet}) and dry mass of sample (m_{dry}):

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

For the bulk density

$$\rho_{bulk} = \frac{m_{dry}}{volume_{cylinder}}$$

the dry mass of the sample is divided by the sample tube volume.

The volumetric water content is the product of the gravimetric water content and the bulk density

$$\theta_v = \theta_g \bullet \rho_{bulk}$$

The average water content for the replicates and the recorded CS650 permittivity are one datum pair to be used for the calibration curve fit.

8.6.3 Collecting field data for calibration

Required equipment:

- CS650 connected to data logger programmed to measure sensor permittivity.
- Cylindrical sampling devices to determine sample volume for bulk density, such as copper tubing with diameter of ≥ 1 inch and length about 2 inches.
- Oven or microwave safe container of known weight.
- Scale to measure soil sample mass.
- Oven or microwave to dry samples.

Data needed for CS650 calibration are the CS650 permittivity output and an independently determined volumetric water content. From this data, the sensor response to changing water content can be described by a function, as described in User-derived calibration equation (p. 26).

The calibration coefficients are derived from a curve fit of known water content and sensor permittivity output. The number of data sets needed to derive a calibration depends on the form of the calibration equation. At least three data sets should be generated to determine whether the linear form is valid. If a polynomial is to be used, four data sets determine whether the function is a quadratic or third order polynomial. Accuracy requirements may need additional data sets. Consider the expected range of soil water content and include data sets from the highest and lowest expected water contents.

Collecting measurements of CS650 permittivity and core samples from the location where the sensor is used provides the best on-site soil-specific calibration. However, intentionally changing water content in soil profiles is difficult.

Soil hydraulic properties are spatially variable. Obtaining measurements that are representative of the soil on a large scale requires multiple readings and sampling. The average of several core samples should be used to calculate volumetric water content. Likewise, the CS650 should be inserted at least three times into the soil recording the permittivities following each insertion and using the average.

The following is the procedure for obtaining samples.

1. Use a shovel to form a vertical face of soil.
2. If using the CS650 within about 0.5 meters of the surface, insert the sensor into the face.
3. Add water to the surface using percolation.
4. Frequently observe the CS650 permittivity output, waiting for the permittivity to be constant. This indicates equilibration.
5. Record the CS650 permittivity.
6. Repeat steps 2 through 5 at least three times.
7. Remove the CS650.
8. Take core samples of the soil using this process:
    a. Evenly push copper tubing into the soil surface.
    b. Remove the tube containing the sample and gently trim the ends of excess soil.
    c. Remove excess soil from outside of tube.

d. Transfer the soil from the tube to the oven or microwave safe container.

> **NOTE:**
> If samples must be stored prior to weighing, seal the container with tape or inside a plastic bag to prevent water loss and store away from direct sunlight.

e. Weigh the container holding the wet soil and subtract the container weight from this value to get the wet soil mass.

f. Record the wet soil mass.

g. Remove water from the sample by heating using an oven or microwave. Oven drying requires 24 hours at 105 °C. Microwave drying typically takes 20 minutes depending on microwave power and sample water content. ASTM Method D4643-93 requires heating in microwave for 3 minutes, cooling in desiccator, then weighing and repeating this process until mass is constant.

h. Weigh the container holding the dry soil and subtract the container weight from this value to get the dry soil mass.

i. Record the dry soil mass.

j. Repeat process to take replicate samples. Three carefully handled samples provide good results.

9. Calculate gravimetric water content from wet mass of sample (m_{wet}) and dry mass of sample (m_{dry}):

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

For the bulk density,

$$\rho_{bulk} = \frac{m_{dry}}{volume_{cylinder}}$$

the dry mass of the sample is divided by the sample tube volume.

The volumetric water content is the product of the gravimetric water content and the bulk density

$$\theta_v = \theta_g \bullet \rho_{bulk}$$

The average water content for the replicates and the recorded CS650 period are one datum pair to be used for the calibration curve fit.

8.6.4 Calculations

The empty cylinders used for core sampling should be clean. Before use, measure and record the empty mass and volume of the cylinders. For a cylinder, the volume is

$$\mathbf{volume} = \pi \bullet \left(\frac{d}{2}\right)^2 \bullet h$$

where d is the inside diameter of the cylinder and h is the height of the cylinder.

During soil sampling, it is important the cores be completely filled with soil, but not extend beyond the ends of the cylinder.

Once soil core samples are obtained, place the soil-filled cylinder in a small tray of known empty mass. This tray holds the core sample during drying in an oven.

To obtain m_{wet}, subtract the cylinder empty mass and the container empty mass from the mass of the soil filled cylinder in the tray. Remove all the soil from the cylinder and place this soil in the tray. Dry the samples using oven or microwave methods, as described earlier.

To obtain m_{dry}, weigh the tray containing the soil after drying. Subtract tray mass for m_{dry}. Calculate gravimetric water content, θ_g, using

$$\theta_g = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

To obtain soil bulk density, use

$$\rho_{bulk} = \frac{m_{dry}}{volume_{cylinder}}$$

Volumetric water content is calculated using

$$\theta_v = \theta_g \bullet \rho_{bulk}$$

9. Maintenance and troubleshooting

The CS650 does not require periodic maintenance. Table 9-1 (p. 33) provides troubleshooting information.

Table 9-1: Symptom, cause, and solutions		
Symptom	Possible cause	Solution
All CS650 output values read 0	No SDI12Recorder instruction in data logger program Conditional statement that triggers reading is not evaluating as true	Add SDI12Recorder instruction to data logger program Check logic of conditional statement that triggers readings
All values read NAN. First value reads NAN and all other values read 0 or never change from one measurement to another	CS650 SDI-12 address does not match address specified in data logger program CS650 green wire not attached to SDI port specified in data logger program CS650 not being powered	Change sensor address or modify program so they match Connect wire to correct control port or modify program to match wiring Make sure red wire is connected to 12V or SW12V and black wire to G If using SW12 to power sensor, make sure red wire is connected and data logger program switches SW12 on
VWC reading is 9999999	Soil bulk permittivity is outside sensor operational range	Modify program to collect permittivity value and try soil specific calibration
EC reading is 9999999	Soil bulk electrical conductivity is outside sensor operational range	If using CS650, try CS655
Readings erratic, including NAN and 9999999	Multiple sensors with same SDI-12 address sharing same control port	Give sensors unique addresses or put on separate control ports

10. References

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Topp, G.C., J.L. Davis & A.P. Annan. 1980. *"Electromagnetic determination of soil water content: measurements in coaxial transmission lines,"* Water Resources Research, v. 16, No. 3:574-582.

Appendix A. Importing *Short Cut* code into *CRBasic Editor*

Short Cut creates a .DEF file that contains wiring information and a program file that can be imported into ***CRBasic Editor***. By default, these files reside in the C:\campbellsci\SCWin folder.

Import ***Short Cut*** program file and wiring information into ***CRBasic Editor***:

1. Create the ***Short Cut*** program, then save it. Click the **Advanced** tab then the **CRBasic Editor** button. Your program file will open in CRBasic with a generic name. Provide a meaningful name and save the CRBasic program. This program can now be edited for additional refinement.

   > **NOTE:**
   > Once the file is edited with ***CRBasic Editor***, ***Short Cut*** can no longer be used to edit the program.

2. To add the ***Short Cut*** wiring information into the new CRBasic program, open the .DEF file located in the C:\campbellsci\SCWin folder. Copy the wiring information found at the beginning of the .DEF file.
3. Go into the CRBasic program and paste the wiring information at the beginning of the program.
4. In the CRBasic program, highlight the wiring information, right-click, and select **Comment Block**. This adds an apostrophe (') to the beginning of each of the highlighted lines, which instructs the data logger compiler to ignore those lines when compiling. The **Comment Block** feature is demonstrated at about 5:10 in the CRBasic | Features video.

Appendix B. Example programs

CRBasic Example 1 (p. 36) measures one CS650 sensor on a CR1000X every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature and samples of permittivity, period average and voltage ratio. The CS650 has an SDI-12 address of 0. Wiring for the example is shown in Table B-1 (p. 36).

Table B-1: CR1000X wiring for one sensor example program

CR1000X	CS650
12V	Red
C1	Green
G	Black, orange, clear

CRBasic Example 1: CR1000X with one CS650 sensor

```
Public CS650(6)
'Assign aliases to the public array
Alias CS650(1)=VWC: Alias CS650(2)=EC: Alias CS650(3)=TSoil
Alias CS650(4)=Perm: Alias CS650(5)=PerAvg: Alias CS650(6)=VoltR
Units VWC = m^3/m^3: Units EC = dS/m: Units TSoil = deg C
DataTable (DatoutCS650,1,-1)
  DataInterval (0,60,Min,10)
  Average (3,CS650(1),FP2,False)
  Sample (3,CS650(4),IEEE4)
EndTable
BeginProg
  Scan (15,Min,0,0)
    SDI12Recorder (CS650(),C1,0,"M4!",1.0,0)
    CallTable DatoutCS650  'Call Data Table
  NextScan
EndProg
```

CRBasic Example 2 (p. 37) measures two CS650 sensors on a CR1000X every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature and samples of permittivity, period average and voltage ratio. The first CS650 has an SDI-12 address of 0 and the second has an address of 1. Wiring for the example is shown in Table B-2 (p. 37). Assignment of aliases and units is not shown in this example.

Table B-2: CR1000X wiring for two sensor example program

CR1000X	CS650 (wiring same for both)
12V	Red
C1	Green
G	Black, orange, clear

CRBasic Example 2: CR1000X with two CS650 sensors on same control port

```
Public CS650(6)
Public CS650_2(6)
DataTable (DatoutCS650,1,-1)
  DataInterval (0,60,Min,10)
  Average (3,CS650(1),FP2,False)
  Sample (3,CS650(4),IEEE4)
  Average (3,CS650_2(1),FP2,False)
  Sample (3,CS650_2(4),IEEE4)
EndTable
BeginProg
  Scan (15,Min,0,0)
    SDI12Recorder (CS650(),C1,0,"M4!",1.0,0)  'Measure CS650 with address 0
    SDI12Recorder (CS650_2(1),C1,1,"M4!",1.0,0)  'Measure CS650 with address 1
    CallTable DatoutCS650  'Call Data Table
  NextScan
EndProg
```

CRBasic Example 3 (p. 39) measures 12 CS650 sensors on a AM16/32B multiplexer every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, soil temperature, permittivity, period average, and voltage ratio. All sensors are addressed with SDI-12 address of 0. In this example, the sensors are powered through the switched 12V terminal and require 3 seconds warm-up time per sensor. Total time to measure all 12 sensors is more than 36 seconds. Alternately, all of the red wires for the sensors could be connected to a bus separate from the multiplexer with the bus connected to 12V for continuous power. This would decrease measurement time. Wiring for the example is shown in Table B-3 (p. 38). Assignment of aliases and units is not shown in this example.

Table B-3: CR1000X wiring for multiplexer example program

CR1000X	AM16/32B (2x32 mode)	CS650
12V	12V	
G	GND	
C2	RES	
C3	CLK	
SW12	COM ODD H	
C1	COM ODD L	
G	COM Ground	
	High terminals 1H – 12H	Red
	Low terminals 1L – 12L	Green
	Ground terminals to left of low terminals	Black, orange, clear

CRBasic Example 3: CR1000X with 12 CS650 sensors on multiplexer

```
Dim LCount
Public CS650(12,6)

DataTable (DatoutCS650,1,-1)
  DataInterval (0,60,Min,2)
  Average (72,CS650(),IEEE4,False)
EndTable

BeginProg
  Scan (15,Min,0,0)
    PortSet(C2,1)  'Turn AM16/32 Multiplexer On
    Delay(0,150,mSec)
    LCount=1
    SubScan(0,uSec,12)
      PulsePort(C3,10000)  'Switch to next AM16/32 terminal
      SW12 (SW12_1,1)  'Apply power to CS650
      Delay (0,3,Sec)  'Wait three seconds for sensor to warm up
      SDI12Recorder (CS650(LCount,1),C1,0,"M4!",1.0,0)
      LCount=LCount+1
      SW12 (SW12_1,0)  'Remove power from CS650
    NextSubScan
    PortSet(C2,0)  'Turn AM16/32 Multiplexer Off
    Delay(0,150,mSec)
    CallTable DatoutCS650  'Call Data Table
  NextScan
EndProg
```

Appendix C. Discussion of soil water content

The water content reflectometer measures volumetric water content. Soil water content is expressed on a gravimetric and a volumetric basis. To obtain the independently determined volumetric water content, gravimetric water content must first be measured. Gravimetric water content (θg) is the mass of water per mass of dry soil. It is measured by weighing a soil sample (m_{wet}), drying the sample to remove the water, and then weighing the dried soil (m_{dry}).

$$\theta_g = \frac{m_{water}}{m_{soil}} = \frac{m_{wet} - m_{dry}}{m_{dry}}$$

Volumetric water content (θ_v) is the volume of liquid water per volume of soil. Volume is the ratio of mass to density (ρ_b) which gives:

$$\theta_v = \frac{volume_{water}}{volume_{soil}} = \frac{\frac{m_{water}}{\rho_{water}}}{\frac{m_{soil}}{\rho_{soil}}} = \frac{\theta_g \bullet \rho_{soil}}{\rho_{water}}$$

The density of water is close to 1 and often ignored.

Soil bulk density (ρ_{bulk}) is used for ρ_{soil} and is the ratio of soil dry mass to sample volume.

$$\rho_{bulk} = \frac{m_{dry}}{volume_{sample}}$$

Another useful property, soil porosity (ε), is related to soil bulk density, as shown by the following expression.

$$\varepsilon = 1 - \frac{\rho_{bulk}}{\rho_{solid}}$$

The term ρ_{solid} is the density of the soil solid fraction and is approximately 2.65 g cm^{-3}.

Appendix D. SDI-12 sensor support

SDI-12 (Serial Data Interface at 1200 baud) is a protocol developed to simplify sensor and data logger compatibility. Only three wires are necessary — serial data, ground, and 12 V. With unique addresses, multiple SDI-12 sensors can connect to a single SDI-12 terminal on a Campbell Scientific data logger.

This appendix discusses the structure of SDI-12 commands and the process of querying SDI-12 sensors. For more detailed information, refer to version 1.4 of the SDI-12 protocol, available at www.sdi-12.org.

For additional information, refer to the SDI-12 Sensors | Transparent Mode and SDI-12 Sensors | Watch or Sniffer Mode videos and the SDI-12 Sensors Troubleshooting Tips application note.

D.1 SDI-12 command basics

SDI-12 commands have three components:

- **Sensor address (a)** – a single character and the first character of the command. Use the default address of zero (0) unless multiple sensors are connected to the same port.
- **Command body** – an upper case letter (the "command"), optionally followed by one or more alphanumeric qualifiers.
- **Command termination (!)** – an exclamation mark.

An active sensor responds to each command. Responses have several standard forms and always terminate with <CR><LF> (carriage return and line feed). Standard SDI-12 commands are listed in Table D-1 (p. 41).

Table D-1: Campbell Scientific sensor SDI-12 command and response set

Name	Command	Response[1]
Acknowledge Active	`a!`	a<CR><LF>
Send Identification	`aI!`	allccccccccmmmmmmvvvxxx...xx <CR><LF>
Start Verification	`aV!`	atttn <CR><LF>

Table D-1: Campbell Scientific sensor SDI-12 command and response set

Name	Command	Response[1]
Address Query	`?!`	a<CR><LF>
Change Address	`aAb!`	b<CR><LF>
Start Measurement	`aM!` `aM1!...aM9!`	atttn<CR><LF>
Send Data	`aD0!...aD9!`	a<values><CR><LF> or a<values><CRC><CR><LF>

[1] Information on each of these commands is given in the following sections.

D.1.1 Acknowledge active command (a!)

The Acknowledge Active command (`a!`) is used to test a sensor on the SDI-12 bus. An active sensor responds with its address.

D.1.2 Send identification command (aI!)

Sensor identifiers are requested by issuing command `aI!`. The reply is defined by the sensor manufacturer but usually includes the sensor address, SDI-12 version, manufacturer's name, and sensor model information. Serial number or other sensor specific information may also be included.

`aI!`	allccccccccmmmmmmvvvxxx...xx<CR><LF>
a	Sensor SDI-12 address
ll	SDI-12 version number (indicates compatibility)
cccccccc	8-character vendor identification
mmmmmm	6 characters specifying the sensor model
vvv	3 characters specifying the sensor version (operating system)
xxx...xx	Up to 13 optional characters used for a serial number or other specific sensor information that is not relevant for operation of the data logger
<CR><LF>	Terminates the response

Source: *SDI-12: A Serial-Digital Interface Standard for Microprocessor-Based Sensors* (see References).

D.1.3 Start verification command (aV!)

The response to a Start Verification command can include hardware diagnostics, but like the `aI!` command, the response is not standardized.

Command: `aV!`

Response: *atttn<CR><LF>*

a = sensor address

ttt = time, in seconds, until verification information is available

n = the number of values to be returned when one or more subsequent `D!` commands are issued

D.1.4 Address query command (?!)

Command `?!` requests the address of the connected sensor. The sensor replies to the query with the address, *a*. This command should only be used with one sensor on the SDI-12 bus at a time.

D.1.5 Change address command (aAb!)

Multiple SDI-12 sensors can connect to a single SDI-12 terminal on a data logger. Each device on a single terminal must have a unique address.

A sensor address is changed with command `aAb!`, where *a* is the current address and *b* is the new address. For example, to change an address from *0* to *2*, the command is `0A2!`. The sensor responds with the new address *b*, which in this case is 2.

> NOTE:
> Only one sensor should be connected to a particular terminal at a time when changing addresses.

D.1.6 Start measurement commands (aM!)

A measurement is initiated with the `M!` command. The response to each command has the form *atttn<CR><LF>*, where

a = sensor address

ttt = time, in seconds, until measurement data is available. When the data is ready, the sensor notifies the data logger, and the data logger begins issuing `D` commands.

n = the number of values returned when one or more subsequent `D` commands are issued. For the `aM!` command, n is an integer from 0 to 9.

When the aM! is issued, the data logger pauses its operation and waits until either it receives the data from the sensor or the time, *ttt*, expires. Depending on the scan interval of the data logger program and the response time of the sensor, this may cause skipped scans to occur. In this case make sure your scan interval is longer than the longest measurement time (*ttt*).

Table D-2: Example aM! sequence	
0M!	The data logger makes a request to sensor 0 to start a measurement.
00352<CR><LF>	Sensor 0 immediately indicates it will return two values within the next 35 seconds.
0<CR><LF>	Within 35 seconds, sensor 0 indicates it has completed the measurement by sending a service request to the data logger.
0D0!	The data logger immediately issues the first D command to collect data from the sensor.
0+.859+3.54<CR><LF>	The sensor immediately responds with the sensor address and the two values.

D.1.7 Stopping a measurement command

A measurement command (M!) is stopped if it detects a break signal before the measurement is complete. A break signal is sent by the data logger before most commands.

A concurrent measurement command (C!) is aborted when another valid command is sent to the sensor before the measurement time has elapsed.

D.1.8 Send data command (aD0! ... aD9!)

The Send Data command requests data from the sensor. It is issued automatically with every type of measurement command (aM!, aMC!, aC!, aCC!). When the measurement command is aM! or aMC!, the data logger issues the aD0! command once a service request has been received from the sensor or the reported time has expired. When the data logger is issuing concurrent commands (aC! or aCC!), the Send Data command is issued after the required time has elapsed (no service request will be sent by the sensor). In transparent mode (see SDI-12 transparent mode [p. 45]), the user asserts this command to obtain data.

Depending on the type of data returned and the number of values a sensor returns, the data logger may need to issue aD0! up to aD9! to retrieve all data. A sensor may return up to 35 characters of data in response to a D command that follows an M! or MC! command. A sensor may return up to 75 characters of data in response to a D command that follows a C! or CC! command. Data values are separated by plus or minus signs.

Command: `aD0!` (`aD1!` ... `aD9!`)

Response: *a<values><CR><LF>* or *a<values><CRC><CR><LF>*

where:

a = the sensor address

<values> = values returned with a polarity sign (+ or –)

<CR><LF> = terminates the response

<CRC> = 16-bit CRC code appended if data was requested with a`MC!` or `aCC!`.

D.2 SDI-12 transparent mode

System operators can manually interrogate and enter settings in probes using transparent mode. Transparent mode is useful in troubleshooting SDI-12 systems because it allows direct communication with probes. Data logger security may need to be unlocked before activating the transparent mode.

Transparent mode is entered while the computer is communicating with the data logger through a terminal emulator program. It is accessed through Campbell Scientific data logger support software or other terminal emulator programs. Data logger keyboards and displays cannot be used.

The terminal emulator is accessed by navigating to the **Tools** list in ***PC400*** or the **Datalogger** list in the **Connect** screen of ***LoggerNet***.

Watch videos/sdi12-sensors-transparent-mode from our website.

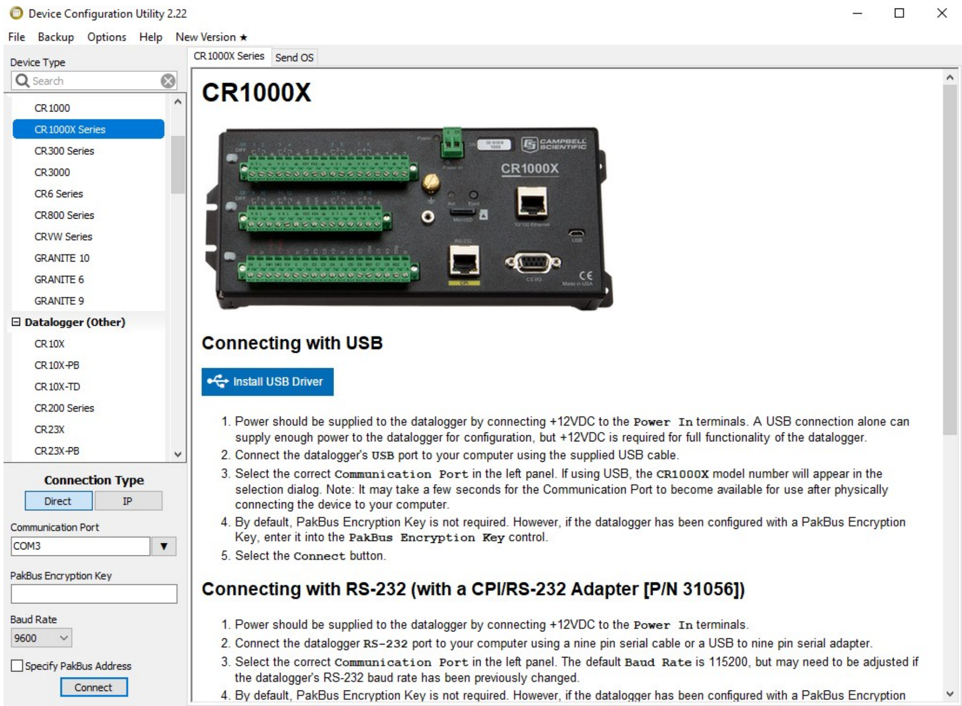
Data loggers from other manufacturers will also have a transparent mode. Refer to those manuals on how to use their transparent mode.

The following examples show how to enter transparent mode and change the SDI-12 address of an SDI-12 sensor. The steps listed are used with most Campbell Scientific data loggers.

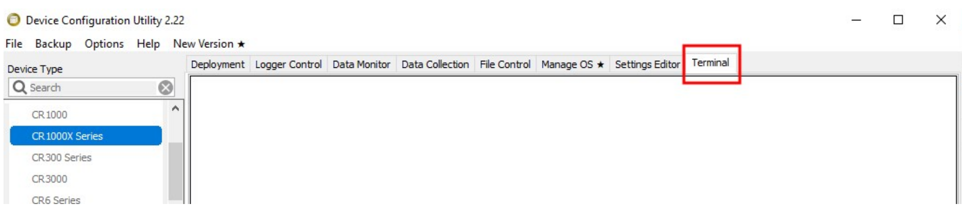
This example was done with a CR1000X, but the steps are only slightly different for CR6, CR3000, CR800-series, CR300-series, and CR1000 data loggers.

1. Connect an SDI-12 sensor to the CR1000X.
2. Open ***Device Configuration*** utility.
3. Under **Device Type**, type the data logger model and double-click on the model type. This example uses a CR1000X directly connected to the computer USB port.

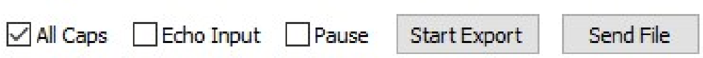
4. Select the correct **Communication Port** and click **Connect**.



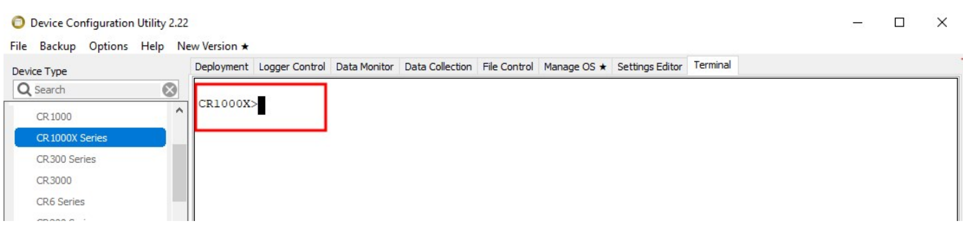
5. Click the **Terminal** tab.



6. Select **All Caps Mode**.



7. Press Enter until the data logger responds with the data logger (**CR1000X>**) prompt.



8. Type **SDI12** and press Enter.

9. At the **Select SDI12 Port** prompt, type the number corresponding to the control port where the sensor is connected and press Enter. In this example, the sensor is connected to C3. The response **Entering SDI12 Terminal** indicates the sensor is ready to accept SDI-12 commands.

```
CR1000X>
CR1000X>SDI12
1: C1
2: C3
3: C5
4: C7
Select SDI12 Port: 2
```

10. To query the sensor for its current SDI-12 address, type **?!** and press Enter. The sensor responds with its SDI-12 address. If no characters are typed within 60 seconds, the mode is exited. In that case, simply type **SDI12** again, press Enter, and type the correct control port number when prompted.

```
?!
0
```

11. To change the SDI-12 address, type **aAb!**, where **a** is the current address from the previous step and **b** is the new address. Press **Enter**. The sensor changes its address and responds with the new address. In the following example, the sensor address is changed from 0 to B.

```
SDI12
SDI12>0AB!B
```

12. To exit SDI-12 transparent mode, click **Close Terminal**.

> NOTE:
> The transparent mode for the CR6, CR3000, CR800-series, CR300-series, and CR1000 data loggers is similar to that shown for the CR1000X.

D.3 References

SDI-12 Support Group. SDI-12: A Serial-Digital Interface Standard for Microprocessor-Based Sensors – Version 1.4. River Heights, UT: SDI-12 Support Group, 2017. https://sdi-12.org/specification.

Appendix E. FAQs

Frequently asked questions

Can the CS650 rods be shortened?

Campbell Scientific strongly discourages shortening the sensor’s rods. The electronics in the sensor head have been optimized to work with the 30 cm long rods. Shortening these rods will change the period average. Consequently, the equations in the firmware will become invalid and give inaccurate readings.

Can the CS650 and the CS655 measure water content between 0 and 0.05?

Probably not. The principle that makes these sensors work is that liquid water has a dielectric permittivity of close to 80, while soil solid particles have a dielectric permittivity of approximately 3 to 6. Because the permittivity of water is over an order of magnitude higher than that of soil solids, water content has a significant impact on the overall bulk dielectric permittivity of the soil. When the soil becomes very dry, that impact is minimized, and it becomes difficult for the sensor to detect small amounts of water. In air dry soil, there is residual water that does not respond to an electric field in the same way as it does when there is enough water to flow among soil pores. Residual water content can range from approximately 0.03 in coarse soils to approximately 0.25 in clay. In the natural environment, water contents below 0.05 indicate that the soil is as dry as it is likely to get. Very small changes in water content will likely cause a change in the sensor period average and permittivity readings, but, to interpret those changes, a very careful calibration using temperature compensation would need to be performed.

Can the CS650 measure permittivity and electrical conductivity of sea water and sea ice?

The electrical conductivity (EC) of sea water is approximately 48 dS/m. The CS650 can measure permittivity in water with EC between 0 and 3 dS/m. EC readings become extremely unstable at conductivities higher than 3 dS/m and are reported as NAN or 9999999. Because EC is part of the permittivity equation, an EC reading of NAN leads to a permittivity reading of NAN as well. Thus, the CS650 cannot provide good readings in sea water.

With regard to sea ice, the electrical conductivity drops significantly when sea water freezes and the permittivity changes from approximately 88 down to approximately 4, as the water changes from a liquid to a solid state. With both EC and permittivity falling to levels that are within the CS650 measurement range, the sensor is expected to give valid readings in sea ice. The sensor is rugged and can withstand the cold temperatures. However, as the ice melts, there will be a point at which the electrical conductivity becomes too high to acquire a valid reading for either permittivity or electrical conductivity.

Do the CS650 and the CS655 have surge protection?

Yes. There is surge protection built into the sensor electronics. The sensor survives a surge of 2 kV at 42 ohm line-to-ground on digital I/O and 2 kV at 12 ohm line-to-ground on power. It also survives a surge of 2 kV at 2 ohm line-to-ground on the rods.

If additional surge protection is required, consider using the SVP100 Surge Voltage Protector DIN Rail with Mounting Hardware.

With the CS650 and the CS655, where is the soil temperature measurement made?

A thermistor is encased in the epoxy head of the sensor next to one of the stainless-steel rods. This provides an accurate point measurement of temperature at the depth where that portion of the sensor head is in contact with the soil. This is why a horizontal placement is the recommended orientation of the CS650 or CS655. The temperature measurement is not averaged over the length of the sensor rods.

Can the CS650 and the CS655 measure water content in greenhouse pots?

Yes, but the pots would have to be large. The CS650 and CS655 can detect water as far away as 10 cm (4 in.) from the rods. If the pot has a diameter smaller than 20 cm (8 in.), the sensor could potentially detect the air around the pot, which would underestimate the water content. In addition, potting soil is typically high in organic matter and clay, causing the probable need for a soil-specific calibration.

Can the CS650 and the CS655 measure gasoline or other hydrocarbons in soil?

No. The principle that makes these sensors work is that liquid water has a dielectric permittivity of close to 80, while soil solid particles have a dielectric permittivity of approximately 3 to 6. Gasoline and other hydrocarbons have dielectric permittivities in the same range as soil particles, which essentially make them invisible to the CS650 and the CS655.

Can the CS650 and the CS655 detect stream bed erosion?

The permittivity of saturated sediments in a stream bed is expected to read somewhere between 25 and 42, while the permittivity of water is close to 80. A CS650 or CS655 installed in saturated sediments could be used to monitor sediment erosion. If the permittivity continuously increases beyond the initial saturated reading, this is an indication that sediment around the sensor rods has eroded and been replaced with water. A calibration could be performed that relates permittivity to the depth of the rods still in the sediment.

How was the general calibration performed for the CS650 and the CS655?

Period average and electrical conductivity readings were taken with several sensors in solutions of varying permittivity and varying electrical conductivity at constant temperature. Coefficients were determined for a best fit of the data. The equation is of the form

$$K_a(\sigma,\tau) = C_0*\sigma^3*\tau^2 + C_1*\sigma^2*\tau^2 + C_2*\sigma*\tau^2 + C_3*\tau^2 + C_4*\sigma^3*\tau + C_5*\sigma^2*\tau + C_6*\sigma*\tau + C_7*\tau + C_8*\sigma^3 + C_9*\sigma^2 + C_{10}*\sigma + C_{11}$$

where Ka is apparent dielectric permittivity, σ is bulk electrical conductivity (dS/m), τ is period average (µS), and C_1 to C_{11} are constants.

Can the CS650 and the CS655 be calibrated by incremental insertion into saturated soil?

No. The abrupt permittivity change at the interface of air and saturated soil causes a different period average response than would occur with the more gradual permittivity change found when the sensor rods are completely inserted in the soil.

For example, if a CS650 or a CS655 was inserted halfway into a saturated soil with a volumetric water content of 0.4, the sensor would provide a different period average and permittivity reading than if the probe was fully inserted into the same soil when it had a volumetric water content of 0.2.

Can the CS650 and the CS655 be repaired?

Damage to the CS650 or the CS655 electronics or rods cannot be repaired because these components are potted in epoxy. Cable damage, on the other hand, may possibly be repaired.

On the CS650 and the CS655, is it possible to disable the logic that causes NAN values?

No. It is not possible to disable the logical tests in the firmware. If soil conditions cause frequent NAN values, it may be possible to perform a soil-specific calibration that will provide good results.

If permittivity is reported but the volumetric water content value is NAN, Campbell Scientific recommends a soil-specific calibration that converts permittivity to water content. This will take advantage of the bulk electrical conductivity correction that occurs in the firmware.

If both permittivity and volumetric water content have NAN values, it may be possible to perform a calibration that converts period average directly to volumetric water content.

Perform a soil-specific calibration. After a soil-specific equation is determined, it may be programmed into the data logger program or used in a spreadsheet to calculate the soil water content.

What is the -VS option for the CS650 and the CS655?

A CS650 or CS655 can be ordered with an SDI-12 address option of -VS. With the -VS option, the SDI-12 address is set at the factory before the sensor is shipped. The last digit of the sensor’s serial number becomes that sensor’s SDI-12 address. Typically, the -VS option is chosen when there are multiple sensors that will communicate with the data logger on the same SDI-12 communications terminal.

If the -VS option is not selected when ordering, the CS650 or CS655 will ship with its SDI-12 address set to 0 (the default -DS option). The address can be changed to a non-zero value using the A200 Sensor to PC Interface or by connecting the sensor to an SDI-12 communications terminal and sending the aAb! Command.

Is it necessary to purchase a DIN Rail Mounting Kit with a CS650 or a CS655?

If a system has multiple CS650 or CS655 sensors, it will be necessary to connect many wires to a 12 V supply and many wires to ground. The DIN Rail Mounting Kit is useful for attaching many wires to the same source in a clean and organized way. For more details, see the 39086 DIN Rail Terminal Kit instruction manual.

Other methods of connecting several wires together, such as terminal strips or wire nuts, would also work.

With the CS650 and the CS655, where is the water content measurement made?

The volumetric water content reading is the average water content over the length of the sensor's rods.

How close to each other can multiple CS650 or CS655 sensors be installed?

CS650 and CS655 sensors are read one at a time using SDI-12 commands. Consequently, they are never active at the same time and do not interfere with each other electrically. When installing the sensors close together, a general guideline is to keep them at least 10 cm apart.

Can the cable for the CS650 or CS655 be shortened?

Modifications to the CS650 or CS655, including shortening the cable, will void the warranty. However, shortening the cable will not affect the sensor's performance. If a decision is made to shorten the cable, care should be taken to avoid damaging the cable jacket and exposing bare wire except at the ends that connect to the data logger or multiplexer terminals.

Can the CS650 and the CS655 measure water content in compost?

Campbell Scientific does not recommend using the CS650 or the CS655 to measure water content in compost. A compost pile is a very hostile environment for making dielectric measurements with soil water content sensors. All of the following combine to make it very difficult to determine a calibration function: high temperature, high and varying electrical conductivity, high organic matter content, heterogeneity of the material in the pile, changing particle size, and changing bulk density. The temperature and electrical conductivity values reported by the CS650 or CS655 may give some useful information about processes occurring in the compost pile, but these sensors will not be able to give useful readings for water content.

Can the CS650 and the CS655 measure water content in gravel?

Yes. Keeping the sensor rods parallel during installation is especially difficult in gravel, but it can be done. Gravel has large pore spaces that drain quickly, so the water content readings will likely show rapid changes between saturation and very dry. If small changes of water content at the dry end are of interest, a soil-specific calibration may need to be performed to convert period average directly to volumetric water content.

Can the CS650 and the CS655 measure water level?

The CS650 and the CS655 are not ideal sensors for measuring water level. However, these sensors do respond to the abrupt change in permittivity at the air/water interface. A calibration could be performed to relate the period average or permittivity reading to the distance along the sensor rods where the air/water interface is located. From that, the water level can be determined. The permittivity of water is temperature dependent, so a temperature correction would be needed to acquire accurate results.

With regard to the CS650 and the CS655, is there a generic calibration equation for artificial or organic soil?

No. The equation used to determine volumetric water content in the firmware for the CS650 and the CS655 is the Topp et al. (1980) equation, which works for a wide range of mineral soils but not necessarily for artificial or organic soils that typically have high organic matter content and high clay content. In this type of soil, the standard equations in the firmware will overestimate water content.

When using a CS650 or a CS655 in artificial or organic soil, it is best to perform a soil-specific calibration. A linear or quadratic equation that relates period average to volumetric water content will work well.

Can the cable length for a CS650 or a CS655 really be up to 2,000 ft?

The cable properties and power requirements of the CS650 and the CS655 are such that communication with a data logger may work for cable lengths greater than 2,000 ft. If multiple sensors are communicating through the same universal or control terminal, the total length of all of those sensors must not exceed 2,000 ft.

In practice, it is less expensive to purchase a new data logger than to buy a CS650 or CS655 with 2,000 ft of cable. If the cable is run through conduit, or if a 2,000 ft long trench needs to be excavated, then the installation cost becomes more expensive than buying another data acquisition system and sensors with shorter cables.

Can the CS650 or the CS655 be partially inserted into the soil?

Because the reported volumetric water content reading is an average taken along the entire length of the rods, the sensor should be fully inserted into the soil. Otherwise, the reading will be the average of both the air and the soil, which will lead to an underestimation of water content. If the sensor rods are too long to go all the way into the soil, Campbell Scientific recommends inserting the rods at an angle until they are fully covered by soil.

When a CS650 or a CS655 is put in water, why does the volumetric water content read NAN?

The dielectric of water at room temperature is close to 80. The firmware for both the CS650 and the CS655 is programmed to change volumetric water content to NAN or 9999999 when the permittivity measurements are greater than 42. When testing in water, look at the permittivity reading rather than the water content reading. If a test is being done for functionality, pull the sensor about halfway out of the water to see both permittivity and volumetric water content readings.

When is it more suitable to use a CS650 rather than a CS655?

In soil that is sandy, sandy loam, or loamy sand with low electrical conductivity, the CS650 is a suitable option because it has slightly better accuracy specifications than the CS655 and a larger measurement volume.

When is it more suitable to use a CS655 rather than a CS650?

In soil that has a significant fraction of fines (loam, silt loam, silty clay loam, clay loam, clay), the CS655 is a suitable option because these soils tend to be more electrically conductive, and the CS655 operates over a larger range of electrical conductivity than the CS650. In applications where a smaller measurement volume is desired, such as larger greenhouse pots, the 12 cm long rods of the CS655 are preferable to the 30 cm long rods of the CS650.

With the CS650 and the CS655, where is the electrical conductivity measurement made?

The bulk electrical conductivity (EC) measurement is made along the sensor rods, and it is an average reading of EC over that distance at whatever depth the rods are placed.

How can it be determined if soil is out-of-bounds for a CS650 or a CS655?

If information is available on soil texture, organic matter content, and electrical conductivity (EC) from soil surveys or lab testing of the soil, it should be possible to tell if the soil conditions fall outside the range of operation of the sensor. Without this information, an educated guess can be made based on soil texture, climate, and management:

- Soil that is coarse textured (such as sand, loamy sand, or sandy loam) works well with a CS650 if the EC is low.
- If the soil is located in an arid or semiarid region, it may have high EC.
- If the soil is frequently fertilized or irrigated with water that has higher EC, it may have high EC.
- If the climate provides enough rain to flush accumulated salts below the root zone, the EC is expected to be low and suitable for a CS650.

When in doubt about soil texture and electrical conductivity, Campbell Scientific recommends using a CS655 because of the sensor's wider range of operation in electrically conductive soils, as compared with the CS650.

Can the CS650 and the CS655 measure water content in mine tailings?

Mine tailings are highly corrosive and have high electrical conductivity. Some customers have successfully used water content reflectometers, such as the CS650 or the CS655, to measure water content in mine tailings by coating the sensor rods with heat-shrink tubing. This affects the sensor output, and a soil-specific calibration must be performed. Care must be taken during installation to avoid damaging the heat-shrink tubing and exposing the sensor's rods. In addition, covering the sensor's rods invalidates the bulk electrical conductivity reading. Unless the temperature reading provided by the CS650 or the CS655 is necessary, a better option may be to use a CS616 with coated rods.

How are the CS650 and the CS655 different?

The CS650 has rods that are 30 cm long, and the CS655 has rods that are 12 cm long. The difference in rod length causes some changes in specifications. For example, the CS650 is slightly more accurate in its permittivity and water content readings, but the CS655 works over a larger range of electrical conductivity. In addition, the CS650 handles a larger measurement volume and provides good accuracy in low EC (electrical conductivity) sand and sandy loam. The CS655 is typically more accurate in soil, works well over a wide range of soil textures and EC, and is easier to install because of its shorter rods.

Why is the electrical conductivity (EC) reading NAN or 9999999 on a CS650 or a CS655?

When the voltage ratio value is greater than 17, the bulk EC reading is reported as NAN or 9999999. This reading also causes the permittivity and volumetric water content values to be NAN or 9999999.

How important is it to install the CS650 or CS655 with the rods exactly parallel?

The CS650 and CS655 work best when the rods are inserted into the soil as parallel to each other as possible. To make parallel pilot holes before installation, use the CS650G Rod Insertion Guide Tool. Minor deflection of a rod during insertion, such as when it contacts a small stone or root, may not affect the readings significantly, but major deflections may cause the CS650 or CS655 to operate outside of published accuracy specifications.

Is it necessary to purchase the CS650G Rod Insertion Guide Tool with a CS650 or CS655?

If the soil is rocky, dry, or hard, Campbell Scientific recommends using a CS650G to make pilot holes before installing the sensor into the soil. When the soil is free of rocks, moderate to very wet, and relatively soft, it is usually possible to install the sensor rods and keep them parallel using gentle and steady pressure on the sensor head.

Note: Never forcefully strike the sensor head with a hammer or step on the sensor head to force the rods into the soil.

How can it be determined if the NAN values are caused by soil conditions or a faulty CS650 or CS655 sensor?

Three of the values returned by the M3! command are never changed to NAN by logical tests. If non-zero readings for soil temperature, period average, and voltage ratio are displayed, the sensor is working.

A simple test in air and water will also show whether the CS650 or CS655 is functioning. When performing this test, look at the permittivity value and not the water content value. In air, the sensor will read a permittivity value of 1. In room-temperature water, the value should be close to 80. The water container should have a diameter of at least 20 cm (8 in.) and a depth of 33 cm (13 in.). A smaller container will result in a lower permittivity value because the sensor will be measuring some of the air outside the container as well as the water. Tap water is acceptable for this test.

Can the CS650 and the CS655 measure water content in frozen soil?

No. The principle that makes these sensors work is that liquid water has a dielectric permittivity of close to 80, while soil solid particles have a dielectric permittivity of approximately 3 to 6. When liquid water freezes, its dielectric permittivity drops to 3.8, essentially making it look like soil particles to the sensor. A CS650 or CS655 installed in soil that freezes would show a rapid decline in its volumetric water content reading with corresponding temperature readings that are below 0°C. As the soil freezes down below the measurement range of the sensor, the water content values would stop changing and remain steady for as long as the soil remains frozen.

How can the CS650 or the CS655 readings be corrected for temperature?

This manual gives a temperature correction that works in coarse sand, but it should be used cautiously with other soil types. If a temperature correction is required, it is best to determine a soil-specific temperature correction.

When correcting for temperature, the following effects contribute to the sensor output:

- The effect of temperature on the measurement electronics inside the sensor head. This is a relatively small effect compared to other temperature effects.
- The change in the dielectric permittivity of water with temperature. At 0°C, the permittivity of water is approximately 88, at 20°C it is approximately 80, and at 70°C it is approximately 64. If the sensor is in a soil at any given water content, the changing permittivity of water will cause the period average at 0°C to be higher than it is at 20°C. The same soil will have a lower period average at 70°C than at 20°C. In other words, the sensor will overestimate water content at colder temperatures and underestimate it at warmer temperatures. However, that is only true if electrical conductivity is negligible.
- The change in water content as bound water is captured and released. In soils with high clay content, some of the water is partially or fully immobilized by electrical charges on the surface of the clay minerals. The amount of bound water is temperature dependent and may have a small effect on the sensor readings.
- The temperature effect of bulk electrical conductivity (EC) on period average. Bulk electrical conductivity increases with temperature; as it increases, it slows down the period average.

The interaction of these effects may be complicated. For example, with increasing temperature, two things happen at the same time: the falling permittivity of water is decreasing the period average, and the increasing EC is increasing the period average. The net result as to whether the period average goes up or down depends on how conductive the soil is and the contributions of the other temperature effects.

How close to the soil surface can a CS650 or a CS655 be installed?

Both the CS650 and the CS655 can detect water as far away as 10 cm in wet sand. That distance decreases as the soil dries down to approximately 4 cm in dry sand. In practice, a depth of 5 cm will give a water content reading that is within the sensor accuracy specification even if a small amount of air near the soil surface is detected and averaged into the reading.

Note: Campbell Scientific does not recommend installing the sensor in a depth shallower than 5 cm.

Can the CS650 and the CS655 measure water content in concrete?

Some customers have successfully used water content reflectometers, such as the CS650 and the CS655, to measure water content of wet concrete mix to ensure consistency between different batches of concrete. However, after concrete begins the curing process, salts are formed that make the electrical conductivity too high for the CS650 and the CS655 to operate. Thus, these sensors cannot be embedded in wet concrete to measure the water content of the concrete as it cures and dries.

How can the cable for the CS650 or CS655 be protected from damage?

Running the cable through electrical conduit or PVC pipe will protect the cable from rodents. A trench 30 to 60 cm deep will protect it from most other human or animal activity. Some customers have found that extra cable can be coiled and left inside a box, such as an irrigation valve box or something similar. When using a box, seal any holes that are large enough for rodents to enter. When cables are exposed on the ground surface, some customers have found that wrapping the cables in the metal screening used for screen doors discourages animals from chewing on them.

Do the CS650 and the CS655 correct readings for temperature changes?

No. The temperature sensor is located inside the sensor's epoxy head next to one of the sensor rods. The stainless-steel rods are not thermally conductive, so the reported soil temperature reading is actually the temperature of the sensor head. If the CS650 or the

CS655 is installed horizontally, which is the preferred method, then the sensor head will be at the same temperature as the soil, and the soil temperature value will be accurate. However, if the sensor is installed vertically, and/or with the sensor head above ground, the soil temperature reading will be less accurate. Because the sensor orientation is not known, no temperature correction was written into the firmware.

Does the cable for the CS650 or CS655 have to go in conduit?

The cable for the sensors is rugged and resistant to damage from the sun and typical weather conditions. However, it is susceptible to damage from rodents, machinery, shovels, and so forth. Running the cable through electrical conduit or PVC pipe will help protect it, but this is not an absolute requirement. In areas where rodent activity is low, direct burial in a trench is usually sufficient. A particularly vulnerable location is where the buried cables exit the ground and enter the enclosure housing the data logger. At that exit point, take steps to protect the cable from damage.

Is it necessary to purchase the A200 with a CS650 or a CS655?

While not necessarily required, an A200 Sensor to PC Interface is useful for connecting a computer directly to the CS650 or CS655 for diagnosis, changing the SDI-12 address, uploading new firmware, and verifying sensor functionality. Typically, only one A200 needs to be purchased unless multiple users with multiple computers need to perform these tasks.

How long will a CS650 or a CS655 last?

The CS650-series sensors have the same rugged epoxy and stainless-steel rods that have been used for water content reflectometers since the CS615-L model was introduced in 1995. There are CS615-L and CS616 sensors in many locations that have been in continuous use for more than ten years with no reported problems. If a CS650 or CS655 remains undamaged by external forces such as lightning, harsh chemicals, or animal actions, the sensor is expected to continue working for decades.

Using a CS650 or a CS655, when should a soil-specific calibration be performed?

To get accurate water content readings, a soil-specific calibration is probably required if any of the following are true:

- The soil has more than 5% organic matter content.
- The soil has more than 20% clay content.
- The soil is derived from volcanic parent material.
- The soil has porosity greater than 0.5.

Can more than 10 CS650 or CS655 sensors be put on the same data logger terminal?

Yes. Because there are a total of 62 available SDI-12 addresses (0 to 9, a to z, A to Z), it would be possible to communicate on the same universal terminal or control port with 62 sensors if each one had a unique address.

In the specifications for the CS650 and the CS655, a limit is stated of 10 sensors per universal terminal or control port because the -VS option gives the sensor an SDI-12 address that matches the last digit of its serial number. That limits the available addresses to 0 to 9, for a total of 10 available addresses. To use addresses a to z or A to Z, change the sensor address with an A200 Sensor to PC Interface or with terminal commands.

Limited warranty

Covered equipment is warranted/guaranteed against defects in materials and workmanship under normal use and service for the period listed on your sales invoice or the product order information web page. The covered period begins on the date of shipment unless otherwise specified. For a repair to be covered under warranty, the following criteria must be met:

1. There must be a defect in materials or workmanship that affects form, fit, or function of the device.

2. The defect cannot be the result of misuse.

3. The defect must have occurred within a specified period of time; and

4. The determination must be made by a qualified technician at a Campbell Scientific Service Center/ repair facility.

The following is not covered:

1. Equipment which has been modified or altered in any way without the written permission of Campbell Scientific.

2. Batteries; and

3. Any equipment which has been subjected to misuse, neglect, acts of God or damage in transit.

Campbell Scientific regional offices handle repairs for customers within their territories. Please see the back page of the manual for a list of regional offices or visit www.campbellsci.com/contact to determine which Campbell Scientific office serves your country. For directions on how to return equipment, see Assistance.

Other manufacturer's products, that are resold by Campbell Scientific, are warranted only to the limits extended by the original manufacturer.

CAMPBELL SCIENTIFIC EXPRESSLY DISCLAIMS AND EXCLUDES ANY IMPLIED WARRANTIES OF

MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. Campbell Scientific hereby disclaims, to the fullest extent allowed by applicable law, any and all warranties and conditions with respect to the products, whether express, implied, or statutory, other than those expressly provided herein.

Campbell Scientific will, as a default, return warranted equipment by surface carrier prepaid. However, the method of return shipment is at Campbell Scientific's sole discretion. Campbell Scientific will not reimburse the claimant for costs incurred in removing and/or reinstalling equipment. This warranty and the Company’s obligation thereunder is in lieu of all other warranties, expressed or implied, including those of suitability and fitness for a particular purpose. Campbell Scientific is not liable for consequential damage.

In the event of any conflict or inconsistency between the provisions of this Warranty and the provisions of Campbell Scientific's Terms, the provisions of Campbell Scientific's Terms shall prevail. Furthermore, Campbell Scientific's Terms are hereby incorporated by reference into this Warranty. To view Terms and conditions that apply to Campbell Scientific, Logan, UT, USA, see Terms and Conditions. To view terms and conditions that apply to Campbell Scientific offices outside of the United States, contact the regional office that serves your country.

Assistance

Products may not be returned without prior authorization. Please inform us before returning equipment and obtain a **return material authorization (RMA) number** whether the repair is under warranty/guarantee or not. See Limited warranty for information on covered equipment.

Campbell Scientific regional offices handle repairs for customers within their territories. Please see the back page of the manual for a list of regional offices or visit www.campbellsci.com/contact to determine which Campbell Scientific office serves your country.

When returning equipment, a RMA number must be clearly marked on the outside of the package. Please state the faults as clearly as possible. Quotations for repairs can be given on request.

It is the policy of Campbell Scientific to protect the health of its employees and provide a safe working environment. In support of this policy, when equipment is returned to Campbell Scientific, Logan, UT, USA, it is mandatory that a "Declaration of Hazardous Material and Decontamination" form be received before the return can be processed. If the form is not received within 5 working days of product receipt or is incomplete, the product will be returned to the customer at the customer's expense. For details on decontamination standards specific to your country, please reach out to your regional Campbell Scientific office.

> NOTE:
> All goods that cross trade boundaries may be subject to some form of fee (customs clearance, duties or import tax). Also, some regional offices require a purchase order upfront if a product is out of the warranty period. Please contact your regional Campbell Scientific office for details.

Safety

DANGER — MANY HAZARDS ARE ASSOCIATED WITH INSTALLING, USING, MAINTAINING, AND WORKING ON OR AROUND TRIPODS, TOWERS, AND ANY ATTACHMENTS TO TRIPODS AND TOWERS SUCH AS SENSORS, CROSSARMS, ENCLOSURES, ANTENNAS, ETC. FAILURE TO PROPERLY AND COMPLETELY ASSEMBLE, INSTALL, OPERATE, USE, AND MAINTAIN TRIPODS, TOWERS, AND ATTACHMENTS, AND FAILURE TO HEED WARNINGS, INCREASES THE RISK OF DEATH, ACCIDENT, SERIOUS INJURY, PROPERTY DAMAGE, AND PRODUCT FAILURE. TAKE ALL REASONABLE PRECAUTIONS TO AVOID THESE HAZARDS. CHECK WITH YOUR ORGANIZATION'S SAFETY COORDINATOR (OR POLICY) FOR PROCEDURES AND REQUIRED PROTECTIVE EQUIPMENT PRIOR TO PERFORMING ANY WORK.

Use tripods, towers, and attachments to tripods and towers only for purposes for which they are designed. Do not exceed design limits. Be familiar and comply with all instructions provided in product manuals. Manuals are available at www.campbellsci.com You are responsible for conformance with governing codes and regulations, including safety regulations, and the integrity and location of structures or land to which towers, tripods, and any attachments are attached. Installation sites should be evaluated and approved by a qualified engineer. If questions or concerns arise regarding installation, use, or maintenance of tripods, towers, attachments, or electrical connections, consult with a licensed and qualified engineer or electrician.

General

- Protect from over-voltage.
- Protect electrical equipment from water.
- Protect from electrostatic discharge (ESD).
- Protect from lightning.
- Prior to performing site or installation work, obtain required approvals and permits. Comply with all governing structure-height regulations, such as those of the FAA in the USA.
- Use only qualified personnel for installation, use, and maintenance of tripods and towers, and any attachments to tripods and towers. The use of licensed and qualified contractors is highly recommended.
- Read all applicable instructions carefully and understand procedures thoroughly before beginning work.
- Wear a hardhat and eye protection, and take other appropriate safety precautions while working on or around tripods and towers.
- Do not climb tripods or towers at any time, and prohibit climbing by other persons. Take reasonable precautions to secure tripod and tower sites from trespassers.
- Use only manufacturer recommended parts, materials, and tools.

Utility and Electrical

- You can be killed or sustain serious bodily injury if the tripod, tower, or attachments you are installing, constructing, using, or maintaining, or a tool, stake, or anchor, come in contact with overhead or underground utility lines.
- Maintain a distance of at least one-and-one-half times structure height, 6 meters (20 feet), or the distance required by applicable law, whichever is greater, between overhead utility lines and the structure (tripod, tower, attachments, or tools).
- Prior to performing site or installation work, inform all utility companies and have all underground utilities marked.
- Comply with all electrical codes. Electrical equipment and related grounding devices should be installed by a licensed and qualified electrician.
- Only use power sources approved for use in the country of installation to power Campbell Scientific devices.

Elevated Work and Weather

- Exercise extreme caution when performing elevated work.
- Use appropriate equipment and safety practices.
- During installation and maintenance, keep tower and tripod sites clear of un-trained or non-essential personnel. Take precautions to prevent elevated tools and objects from dropping.
- Do not perform any work in inclement weather, including wind, rain, snow, lightning, etc.

Internal Battery

- Be aware of fire, explosion, and severe-burn hazards.
- Misuse or improper installation of the internal lithium battery can cause severe injury.

- Do not recharge, disassemble, heat above 100 °C (212 °F), solder directly to the cell, incinerate, or expose contents to water. Dispose of spent batteries properly.

Use and disposal of batteries

- Where batteries need to be transported to the installation site, ensure they are packed to prevent the battery terminals shorting which could cause a fire or explosion. Especially in the case of lithium batteries, ensure they are packed and transported in a way that complies with local shipping regulations and the safety requirements of the carriers involved.
- When installing the batteries follow the installation instructions very carefully. This is to avoid risk of damage to the equipment caused by installing the wrong type of battery or reverse connections.
- When disposing of used batteries, it is still important to avoid the risk of shorting. Do not dispose of the batteries in a fire as there is risk of explosion and leakage of harmful chemicals into the environment. Batteries should be disposed of at registered recycling facilities.

Avoiding unnecessary exposure to radio transmitter radiation

- Where the equipment includes a radio transmitter, precautions should be taken to avoid unnecessary exposure to radiation from the antenna. The degree of caution required varies with the power of the transmitter, but as a rule it is best to avoid getting closer to the antenna than 20 cm (8 inches) when the antenna is active. In particular keep your head away from the antenna. For higher power radios (in excess of 1 W ERP) turn the radio off when servicing the system, unless the antenna is installed away from the station, e.g. it is mounted above the system on an arm or pole.

Maintenance

- Periodically (at least yearly) check for wear and damage, including corrosion, stress cracks, frayed cables, loose cable clamps, cable tightness, etc. and take necessary corrective actions.
- Periodically (at least yearly) check electrical ground connections.

WHILE EVERY ATTEMPT IS MADE TO EMBODY THE HIGHEST DEGREE OF SAFETY IN ALL CAMPBELL SCIENTIFIC PRODUCTS, THE CUSTOMER ASSUMES ALL RISK FROM ANY INJURY RESULTING FROM IMPROPER INSTALLATION, USE, OR MAINTENANCE OF TRIPODS, TOWERS, OR ATTACHMENTS TO TRIPODS AND TOWERS SUCH AS SENSORS, CROSSARMS, ENCLOSURES, ANTENNAS, ETC.

Global Sales and Support Network

A worldwide network to help meet your needs

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