

INSTRUCTION MANUAL



CS650 and CS655 Water Content Reflectometers

Revision: 4/18



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CS650 and CS655 Water Content Reflectometers

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. They output an SDI-12 signal that many Campbell Scientific dataloggers 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 dataloggers. For retired Edlog datalogger support, you can access a retired manual at www.campbellsci.com/old-manuals.

2. Precautions

- READ AND UNDERSTAND the *Safety* section at the front of this manual.
- Although the CS650 is rugged, it should be handled as 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

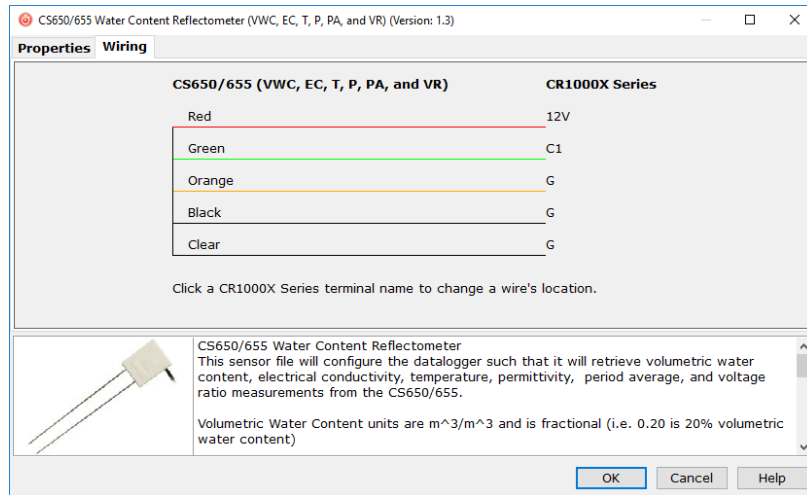
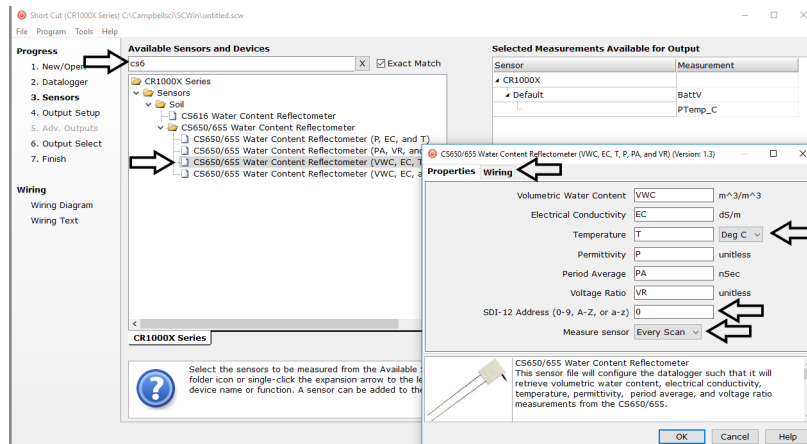
- Upon receipt of the CS650, inspect the packaging and contents for damage. File damage claims with the shipping company.
- The model number and cable length are printed on a label at the connection end of the cable. Check this information against the shipping documents to ensure the expected product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

4. QuickStart

A video that describes datalogger programming using *Short Cut* is available at: www.campbellsci.com/videos/cr1000x-datalogger-getting-started-program-part-3. *Short Cut* is an easy way to program your datalogger to measure the CS650 and assign datalogger wiring terminals. *Short Cut* is available as a download on www.campbellsci.com. It is included in installations of *LoggerNet*, *PC200W*, *PC400*, or *RTDAQ*.

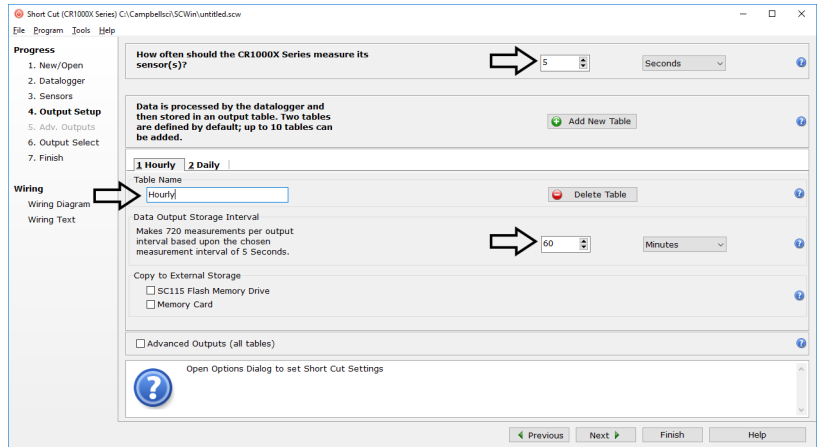
The following procedure also describes programming with *Short Cut*.

1. Open *Short Cut* and click **Create New Program**.
2. Double-click the datalogger 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 datalogger.

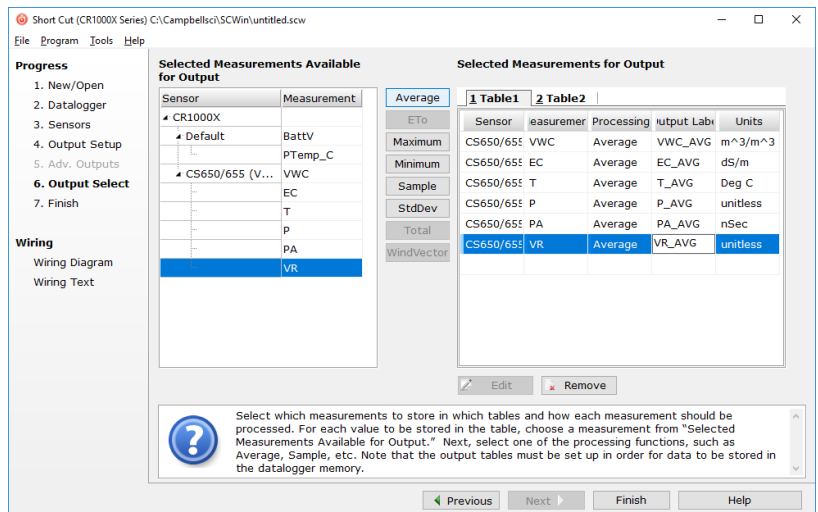


4. Repeat step three for other sensors you want to measure.

- 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**.



- Select the measurement and its associated output options.



- Click **Finish** and save the program. Send the program to the datalogger if the datalogger is connected to the computer.
- If the sensor is connected to the datalogger, check the output of the sensor in the data display in *LoggerNet*, *PC400*, *RTDAQ*, or *PC200W* 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.

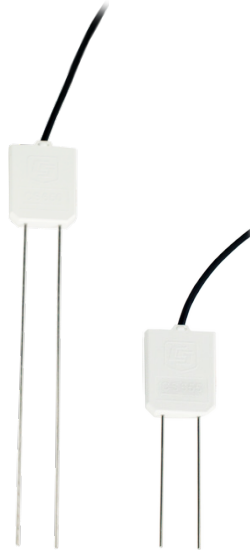


FIGURE 5-1. CS650 (left) and CS655 Water Content Reflectometers

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 is configured as a water content reflectometer, with the two parallel rods forming an open-ended transmission line. A differential oscillator circuit is connected to the rods, with an oscillator state change triggered by the return of a reflected signal from one of the rods. 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 that 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 suffer from unwanted increases in oscillation period as increasing electrical conductivity causes transmission line signal attenuation. 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 signal attenuation measurement and combines the result with the oscillation period measurement to calculate the dielectric permittivity of the media and finally 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 and ground as well as communications with the CS650. The CS650 is intended to communicate with SDI-12 recorders, including Campbell Scientific dataloggers. Alternatively, use the orange wire to transmit and receive RS-232. 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.

6. Specifications

Features:

- Measurement corrected for effects of soil texture and electrical conductivity
- 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 dataloggers: CR200(X) series, CR300 series, CR6 series, CR800 series, CR1000, CR1000X series, CR3000, and CR5000

TABLE 6-1 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 ⁻¹	35 g m ⁻¹

Ingress Protection Rating: IP68

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 Vdc 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 datalogger control or U terminal ¹
Electromagnetic Compatibility:	View EU Declaration of Conformity documentation at www.campbellsci.com/cs650 . External RF sources can affect CS650 measurements. CS650 circuitry should be located away from radio transmitter aerials and cables, or measurements 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)

¹Campbell Scientific recommends using separate terminals when possible.

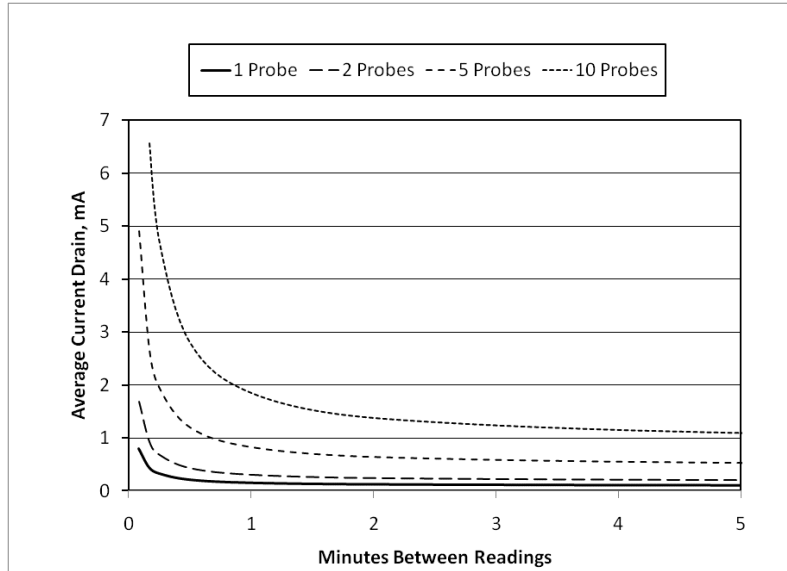


FIGURE 6-1. CS650 and CS655 average current drain

FIGURE 6-1 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 provides the operational specifications.

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

TABLE 6-2. Relative Dielectric Permittivity Specifications		
	CS650	CS655
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
<p>*Sensing Volume approximately 7.5 cm radius around each sensor rod and 4.5 cm beyond the end of the rods</p> <p>†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.</p> <p>‡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.</p>		

7. Installation

If you are programming your datalogger with *Short Cut*, skip Section 7.3, *Datalogger Wiring* (p. 9), and Section 7.4, *Programming* (p. 10). *Short Cut* does this work for you. See Section 4, *QuickStart* (p. 1), for a *Short Cut* tutorial.

7.1 Orientation and Placement

The CS650 measures the bulk dielectric permittivity, average volumetric water content, and bulk 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 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 Datalogger Wiring

Campbell Scientific dataloggers 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 shows the SDI-12 wiring for the CS650 water content reflectometer. SDI-12 data is transmitted to a CRBasic datalogger odd-numbered control or U terminal. Wiring information for RS-232 communications is provided in Section 8.1.1.2, *RS-232 Wiring (p. 11)*.

TABLE 7-1. Wire Color, Function, and Datalogger Connection for SDI-12

Color	Function	Datalogger 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	⊥
Orange	Not Used	G

¹U 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 dataloggers, 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 datalogger programming code.

If your data acquisition requirements are simple, you can probably create and maintain a datalogger 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 Section 4, *QuickStart* (p. 1). Follow the procedure in Appendix A, *Importing Short Cut Code Into CRBasic Editor* (p. A-1) to import *Short Cut* code into *CRBasic Editor* to create or add to a customized program. Programming basics for *CRBasic* dataloggers are provided in this section. Complete program examples for select *CRBasic* dataloggers are provided in Appendix B, *Example Programs* (p. B-1). Programming basics and programming examples for *Edlog* dataloggers are provided at www.campbellsci.com/old-manuals.

Use the **SDI12Recorder()** instruction to measure the sensor. This instruction sends a request to the sensor to make a measurement then retrieves the measurement values from the sensor. See Section 8.2, *SDI-12 Measurements* (p. 16), for more information.

For most CRBasic dataloggers, 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).

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.

8.1.1 Using the A200

8.1.1.1 Driver Installation

If the A200 has not been previously plugged into your computer and your computer operating system is not Windows 7, 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**.

8.1.1.2 RS-232 Wiring

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 and TABLE 8-1).



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

8.1.1.3 Powering the Sensor

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.

8.1.1.4 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.

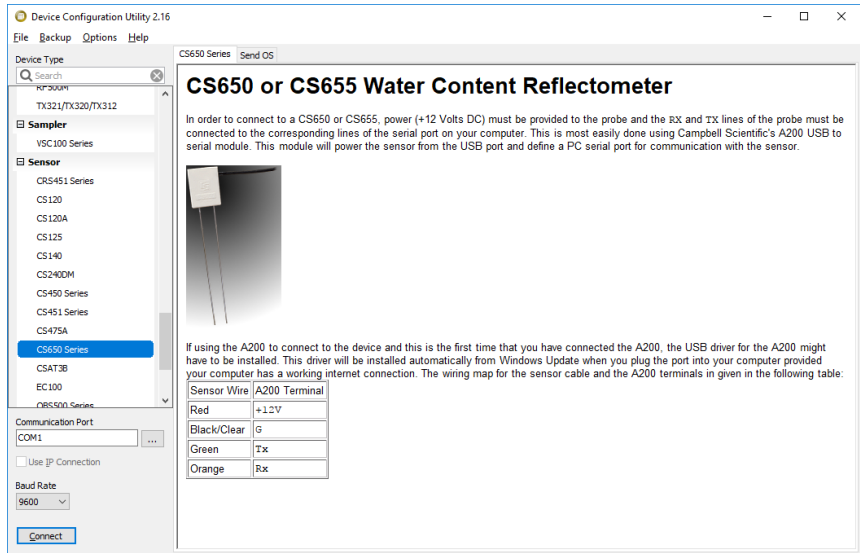
To check which COM port has been assigned to the A200, monitor the appearance of a new COM port in the list of COM ports offered in your software package such as *LoggerNet* before and after the installation, or look in the Windows Device Manager list under the ports section (access via the control panel).

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*, *PC400*, or *RTDAQ*.

Connect the CS650 to the A200 as shown in TABLE 8-1. 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 Section 8.1.1.4, *Determining which COM Port the A200 has been Assigned (p. 12)*).

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). This is useful for verifying sensor performance.

Settings Editor

OS Version
CS65x.Std.00.22

OS Date
March 19, 2010 3:30pm

Model Name
CS650

Serial Number
0

User Name
No User Name

SDI-12 Address
0

RS-232 Baud Rate
9600

Real-Time Measurements
Period(uSec) = 1.459
Voltage Ratio = 1
Dielectric Permittivity = 6.698

Ka Multiplier
30

Ka Offset
2.975228

EC Multiplier
-2.09345

EC Offset
-32.6009

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

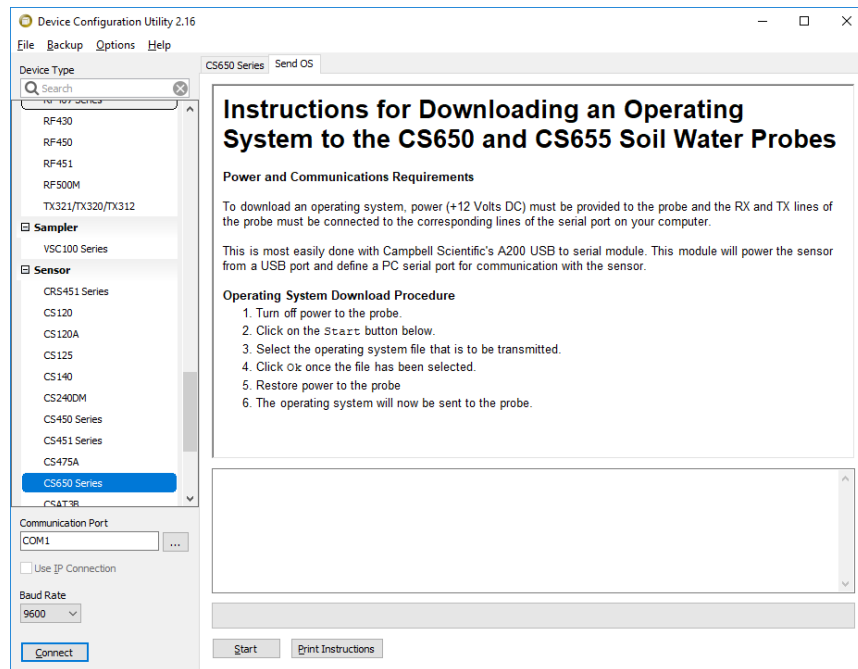
Setting Name	Setting Value														
	CS65x.Std.00.22														
	March 19, 2010 3:30pm														
Model_Name	CS650														
Sensor SN	4,294,967,295														
	No User Name														
SDI-12_Address	0														
Baud_Rate	9600														
Real-Time Measurements	<table border="1">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

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.04.36.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 shows the values returned for each of these commands.

Establish SDI-12 communications using the **SDI12Recorder()** CRBasic instruction. See Section 7.3, *Datalogger Wiring* (p. 9), for SDI-12 wiring details.

NOTE

This section briefly describes using SDI-12 commands. Additional SDI-12 information is available at Appendix D, *SDI-12 Sensor Support* (p. D-1), www.sdi-12.org, or www.youtube.com/user/CampbellScientific.

SDI-12 command ("a" is the sensor address)	Values Returned	Units
aM!	1) Volumetric Water Content, θ 2) Electrical Conductivity, σ 3) Temperature	m^3/m^3 dS/m $^{\circ}C$
aM1!	1) Permittivity, ϵ 2) Electrical Conductivity, σ 3) Temperature	dS/m $^{\circ}C$
aM2!	1) Period, τ 2) Voltage Ratio, α 3) Temperature	μs $^{\circ}C$
aM3!	1) Volumetric Water Content, θ 2) Electrical Conductivity, σ 3) Temperature 4) Permittivity, ϵ 5) Period, τ 6) Voltage Ratio, α	m^3/m^3 dS/m $^{\circ}C$ μs
aM4!	1) Volumetric Water Content, θ 2) Electrical Conductivity, σ 3) Temperature 4) Permittivity, ϵ 5) Period, τ 6) Voltage Ratio, α	m^3/m^3 dS/m $^{\circ}C$ 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 datalogger 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 Section 8.1, *A200 and Device Configuration Utility* (p. 11)) or with a terminal emulator in SDI-12 transparent mode (see Appendix D, *SDI-12 Sensor Support* (p. D-1)).

8.2.1 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 that 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.

8.2.2 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 datalogger 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 Appendix B, *Example Programs (p. B-1)*, show the commands used in CRBasic.

8.3 Water Content Reflectometer Method for Measuring Volumetric Water Content

8.3.1 Description of Measurement Method

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 that 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.

8.3.2 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 that 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 Section 8.4, *Water Content Reflectometer User-Calibration* (p. 22).

8.3.3 Electrical Conductivity

8.3.3.1 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, σ_{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)

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

where σ_{bulk} is the electrical conductivity of the bulk soil; σ_{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 σ_{solution} up to 3 dS m⁻¹ for the CS650 and up to 10 dS m⁻¹ for the CS655. This is equivalent to σ_{bulk} values of approximately 0.8 dS m⁻¹ and 2.7 dS m⁻¹ 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.

8.3.3.2 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:

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

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

8.3.4 Error Sources in Water Content Reflectometer Measurement

8.3.4.1 Sensor-to-Sensor Variability Error

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.

8.3.4.2 Insertion Error

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.

8.3.5 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:

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

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.

8.3.5.1 Accurate Soil Temperature Measurement

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 that it is insulated from diurnal temperature fluctuations.

8.4 Water Content Reflectometer User-Calibration

8.4.1 Need for Soil Specific Calibration Equation

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.

8.4.2 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:

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

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

Third-degree polynomial form:

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

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

Linear form:

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

with θ_v the volumetric water content, K_a the bulk dielectric permittivity of the soil, and C_n , 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.

8.4.3 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 Section 8.4.2, *User-Derived Calibration Equation* (p. 23).

Required equipment:

- CS650 connected to datalogger 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 that 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 that 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 (Section 10, *References* (p. 30)).
 - 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}):

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

For the bulk density

$$\rho_{\text{bulk}} = \frac{m_{\text{dry}}}{\text{volume}_{\text{cylinder}}}$$

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

$$\theta_v = \theta_g \cdot \rho_{\text{bulk}}$$

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

8.4.4 Collecting Field Data for Calibration

Required equipment:

- CS650 connected to datalogger 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 Section 8.4.2, *User-Derived Calibration Equation* (p. 23).

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}):

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

For the bulk density,

$$\rho_{\text{bulk}} = \frac{m_{\text{dry}}}{\text{volume}_{\text{cylinder}}}$$

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

$$\theta_v = \theta_g \cdot \rho_{\text{bulk}}$$

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

8.4.5 Calculations

The empty cylinders used for core sampling should be clean and both empty mass and volume are measured and recorded. For a cylinder, the volume is

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

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

During soil sampling it is important that 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

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

9. Maintenance and Troubleshooting

The CS650 does not require periodic maintenance. TABLE 9-1 provides troubleshooting information.

Symptom	Possible Cause	Solution
All CS650 output values read 0	No SDI12Recorder instruction in datalogger program Conditional statement that triggers reading is not evaluating as true	Add SDI12Recorder instruction to datalogger 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 datalogger program CS650 green wire not attached to SDI port specified in datalogger program CS650 not being powered	Change sensor address or modify program so that 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 datalogger program switches SW12 on

TABLE 9-1. Symptom, Cause, and Solutions		
Symptom	Possible Cause	Solution
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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- Rhoades, J.D., P.A.C. Raats, and R.J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content and surface conductivity on bulk soil electrical conductivity. Soil Sci. Soc. Am. J., 40: 651-653.
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Appendix A. Importing Short Cut Code Into CRBasic Editor

This tutorial shows:

- Importing a *Short Cut* program into a program editor for additional refinement
- Importing a wiring diagram from *Short Cut* into the comments of a custom program

Short Cut creates files, which can be imported into *CRBasic Editor*. Assuming defaults were used when *Short Cut* was installed, these files reside in the C:\campbellsci\SCWin folder:

- .DEF (wiring and memory usage information)
- .CR2 (CR200(X)-series datalogger code)
- .CR300 (CR300-series datalogger code)
- .CR6 (CR6-series datalogger code)
- .CR8 (CR800-series datalogger code)
- .CR1 (CR1000 datalogger code)
- .CR1X (CR1000X-series datalogger code)
- .CR3 (CR3000 datalogger code)
- .CR5 (CR5000 datalogger code)

Import *Short Cut* code and wiring diagram into *CRBasic Editor*:

1. Create the *Short Cut* program following the procedure in Section 4, *QuickStart* (p. 1). Finish the program. On the **Advanced** tab, click the **CRBasic Editor** button. The program opens in CRBasic with the name **noname.CR_**. Provide a name and save the program.

NOTE

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

2. The program can now be edited, saved, and sent to the datalogger.
3. Import wiring information to the program by opening the associated .DEF file. By default, it is saved in the c:\campbellsci\SCWin folder. Copy and paste the section beginning with heading “–Wiring for CRXXX–” into the CRBasic program, usually at the head of the file. After pasting, edit the information such that an apostrophe (') begins each line. This character instructs the datalogger compiler to ignore the line when compiling. You can highlight several lines of CRBasic code then right-click and select **Comment Block**. (This feature is demonstrated at about 5:10 in the [CRBasic | Features](#) video.)

Appendix B. Example Programs

B.1 CR1000X Programs

B.1.1 CR1000X with One CS650 Sensor

This CRBasic example program 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.

TABLE B-1. CR1000X Wiring for One Sensor Example Program

CR1000X	CS650
12V	Red
C1	Green
G	Black, Orange, Clear

CRBasic Example B-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
```

B.1.2 CR1000X with Two CS650 Sensors on Same Control Port

This CRBasic example program 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. Assignment of aliases and units is not shown in this example.

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

```

CRBasic Example B-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
    
```

B.1.3 CR1000X with 12 CS650 Sensors on Multiplexer

This CRBasic example program 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. 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 B-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

```

B.2 CR200X with Three CS650 Sensors

This CRBasic example program measures three CS650 sensors on a CR200X every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, soil temperature, permittivity, period average, and voltage ratio. The CS650s have SDI-12 addresses of 0, 1, and 2, respectively. Sensors are powered with the **SW Battery** terminal, which requires a 3 second warm-up time. Alternately, connect the red wires to Battery + for continuous power which reduces measurement time. Wiring for the example is shown in TABLE B-4. Assignment of aliases and units is not shown in this example.

TABLE B-4. CR200(X) Wiring for Example Program

CR200(X)	CS650s (Wiring same for all)
SW Battery	Red
C1/SDI-12	Green
G terminals	Black, Orange, Clear

CRBasic Example B-4. CR200X with Three CS650 Sensors

```
Public CS650(18)

DataTable (CS650,1,-1)
  DataInterval (0,60,Min)
  Average (18,CS650(),False)
EndTable

BeginProg
  Scan (15,Min)

  SWBatt (1 )      'Apply power to CS650s
  Delay (3,sec)   'Warm-up time of 3 seconds

  'CS650 #1
  SDI12Recorder (CS650(1),"0M4!",1,0)

  'CS650 #2
  SDI12Recorder (CS650(7),"1M4!",1,0)

  'CS650 #3
  SDI12Recorder (CS650(13),"2M4!",1,0)

  SWBatt (0 )      'Remove power from the CS650s
  CallTable CS650  '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 (θ_g) 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, then weighing the dried soil (m_{dry}).

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

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:

$$\theta_v = \frac{\text{volume}_{\text{water}}}{\text{volume}_{\text{soil}}} = \frac{\frac{m_{\text{water}}}{\rho_{\text{water}}}}{\frac{m_{\text{soil}}}{\rho_{\text{soil}}}} = \frac{\theta_g \cdot \rho_{\text{soil}}}{\rho_{\text{water}}}$$

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.

$$\rho_{\text{bulk}} = \frac{m_{\text{dry}}}{\text{volume}_{\text{sample}}}$$

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

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

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

D.1 Introduction

SDI-12, Serial Data Interface at 1200 baud, is a protocol developed to simplify sensor and datalogger 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 datalogger.

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.

D.2 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.

Name	Command	Response¹
Acknowledge Active	a!	a<CR><LF>
Send Identification	aI!	allccccccmmmmmmvvvxxx...xx <CR><LF>
Start Verification	aV!	attn <CR><LF>
Address Query	?!	a<CR><LF>
Change Address	aAb!	b<CR><LF>
Start Measurement	aM! aM1!...aM9!	attn<CR><LF>
Start Measurement and Request CRC	aMC! aMC1!...aMC9!	attn <CR><LF>

TABLE D-1. Campbell Scientific Sensor SDI-12 Command and Response Set		
Name	Command	Response ¹
Send Data	aD0!...aD9!	a<values><CR><LF> or a<values><CRC><CR><LF>
¹ Information on each of these commands is given in following sections.		

D.2.1 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.2.2 Send Identification Command (a!)

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

a!	allccccccmmmmmmvvvxxx...xx<CR><LF>
a	Sensor SDI-12 address
ll	SDI-12 version number (indicates compatibility)
ccccccc	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 datalogger
<CR><LF>	Terminates the response
Source: <i>SDI-12: A Serial-Digital Interface Standard for Microprocessor-Based Sensors</i> (see Appendix D.4, References (p. D-7)).	

D.2.3 Start Verification Command (aV!)

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

Command: **aV!**
Response: *attn*<CR><LF>

a = sensor address

ttn = 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.2.4 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.2.5 Change Address Command (aAb!)

Multiple SDI-12 sensors can connect to a single SDI-12 terminal on a datalogger. 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.

D.2.6 Start Measurement Commands (aM!)

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

a = sensor address

t = time, in seconds, until measurement data is available. When the data is ready, the sensor notifies the datalogger, and the datalogger 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 datalogger pauses its operation and waits until either it receives the data from the sensor or the time, *t*, expires.

Depending on the scan interval of the datalogger 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 (*t*).

TABLE D-2. Example aM! Sequence

0M!	The datalogger makes a request to sensor 0 to start a measurement.
00352<CR><LF>	Sensor 0 immediately indicates that it will return two values within the next 35 seconds.
0<CR><LF>	Within 35 seconds, sensor 0 indicates that it has completed the measurement by sending a service request to the datalogger.
0D0!	The datalogger immediately initiates the process of collecting the sensor data by issuing the first D command.
0+.859+3.54<CR><LF>	The sensor immediately responds with the sensor address and the two values.

D.2.7 Start Measurement Commands with Cyclic Redundancy Check (aMC! !)

Error checking is done by using measurement commands with cyclic redundancy checks (**aMC!**). This is most commonly implemented when long cable lengths or electronic noise may impact measurement transmission to the datalogger. When these commands are used, the data returned in response to **D** commands must have a cyclic redundancy check (CRC) code appended to it. The CRC code is a 16-bit value encoded within 3 characters appended before the `<CR><LF>`. This code is not returned in the data table but checked by the datalogger as it comes. The code returned is based on the SDI-12 protocol. See the SDI-12 communications specification for version 1.3 available at www.sdi-12.org to learn more about how the CRC code is developed.

D.2.8 Stopping a Measurement Command

A measurement command (**M!**) is stopped if it detects a break signal. A break signal is sent by the datalogger 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.2.9 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!**). When the measurement command is **aM!** or **aMC!**, the datalogger issues the **aD0!** command once a service request has been received from the sensor. In transparent mode (Appendix D.3, *SDI-12 Transparent Mode (p. D-4)*), the user asserts this command to obtain data.

Depending on the type of data returned and the number of values a sensor returns, the datalogger 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.

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 **aMC!**

D.3 SDI-12 Transparent Mode

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

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

The terminal emulator is accessed by navigating to the **Datalogger** list in *PC200W*, the **Tools** list in *PC400*, or the **Datalogger** list in the *Connect* screen of *LoggerNet*.



Watch the video: [SDI-12 Sensors | Transparent Mode](#).

The following examples show how to enter transparent mode and change the SDI-12 address of an SDI-12 sensor. The steps shown in Appendix D.3.1, *Changing an SDI-12 Address* (p. D-5), are used with most Campbell Scientific dataloggers. Appendix D.3.2, *Changing an SDI-12 Address – CR200(X) Series* (p. D-6), lists the steps used for CR200(X)-series dataloggers.

D.3.1 Changing an SDI-12 Address

The example below was done with a CR1000, but the steps are only slightly different for CR1000X-series, CR300-series, CR6-series, CR800-series, and CR3000 dataloggers. For CR200(X)-series dataloggers, see Appendix D.3.2, *Changing an SDI-12 Address – CR200(X) Series* (p. D-6).

1. Connect an SDI-12 sensor to the CR1000.
2. In *LoggerNet Connect*, under **Datalogger**, click **Terminal Emulator**. The terminal emulator window opens.
3. Under **Select Device**, located in the lower left side of the window, select the **CR1000** station.
4. Click **Open Terminal**.
5. Select **All Caps Mode**.
6. Press Enter until the datalogger responds with the *CR1000>* prompt.
7. Type **SDI12** and press Enter.
8. At the *Select SDI12 Port* prompt, type the number corresponding to the control port where the sensor is connected and press Enter. The response *Entering SDI12 Terminal* indicates that the sensor is ready to accept SDI-12 commands.
9. 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.
10. To change the SDI-12 address, type **aAb!**, where *a* is the current address from the above step and *b* is the new address (see FIGURE D-1). Press Enter. The sensor changes its address and responds with the new address.

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

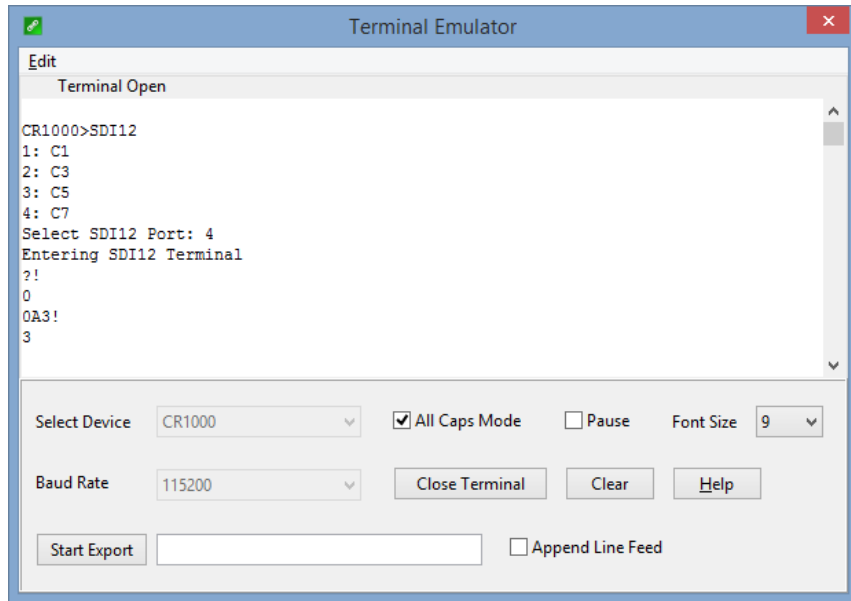


FIGURE D-1. CR1000 example of using the SDI-12 transparent mode to change the SDI-12 address from 0 to 3. Sensor is connected to control port 1.

D.3.2 Changing an SDI-12 Address – CR200(X) Series

1. Connect a single SDI-12 sensor to the CR200(X).
2. In *LoggerNet Connect*, under **Datalogger**, click **Terminal Emulator**. The terminal emulator window opens.
3. Under **Select Device**, located in the lower left side of the window, select the **CR200Series** station.
4. Click **Open Terminal**.
5. Select **All Caps Mode**.
6. Press Enter until the datalogger responds with the *CR2XX>* prompt.
7. Type **SDI12** and press Enter.
8. The response *SDI12>* indicates that the sensor is ready to accept SDI-12 commands.
9. 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 and press Enter.

10. To change the SDI-12 address, type **aAb!**, where *a* is the current address from the above step and *b* is the new address (see FIGURE D-1). Press Enter. The sensor changes its address and responds with the new address.
11. To exit SDI-12 transparent mode, click **Close Terminal**.

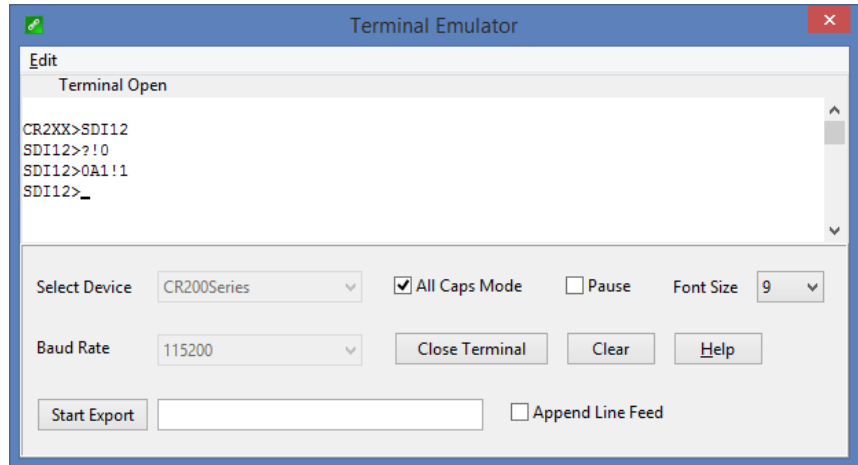


FIGURE D-2. CR200(X) example of using the SDI-12 transparent mode to change the SDI-12 address from 0 to 1

D.4 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. www.sdi-12.org/specification.php?file_id=1.

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