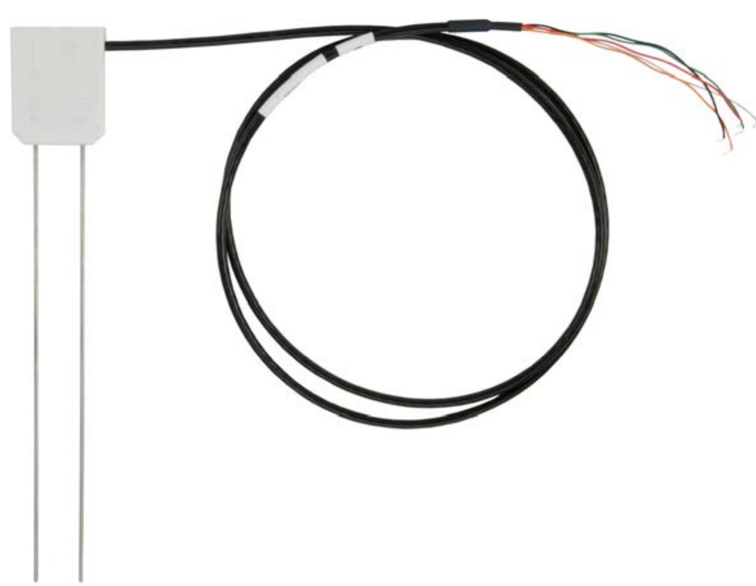
INSTRUCTION MANUAL

CS650 and CS655 Water Content Reflectometers

Revision: 11/11



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PLEASE READ FIRST

About this manual

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

Some useful conversion factors:

Area:	1 in^2 (square inch) = 645 mm^2
Length:	1 in. (inch) = 25.4 mm 1 ft (foot) = 304.8 mm 1 yard = 0.914 m 1 mile = 1.609 km
Mass:	1 oz. (ounce) = 28.35 g 1 lb (pound weight) = 0.454 kg
Pressure:	1 psi (lb/in2) = 68.95 mb
Volume:	1 US gallon = 3.785 litres

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

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CS650 and CS655 Water Content Reflectometers

1. General Description

The CS650 and CS655 Water Content Reflectometers measure volumetric water content, electrical conductivity, dielectric permittivity, and temperature of soils or other porous media. These values are reported through SDI-12 communication. 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.

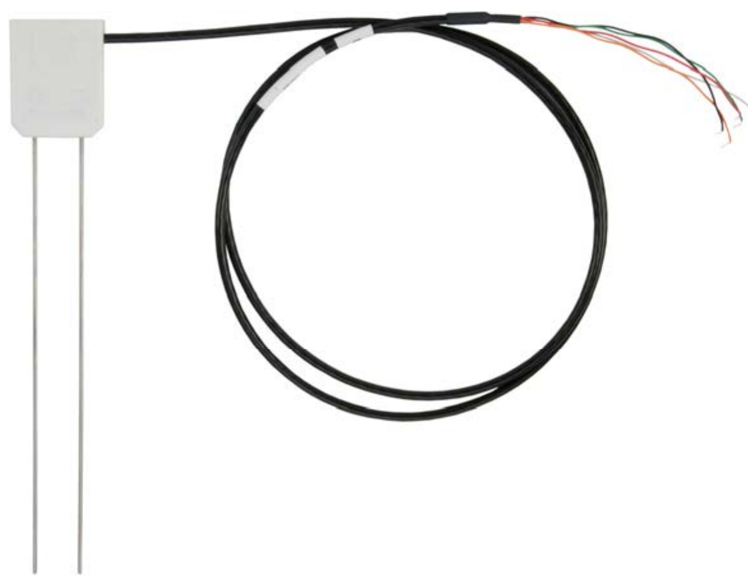


FIGURE 1-1. CS650 Water Content Reflectometer

Volumetric water content information is derived from the probe's sensitivity to the dielectric permittivity of the medium surrounding the probe 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.

Electrical conductivity is determined by exciting the rods with a known non-polarizing waveform and measuring the signal attenuation.

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 and 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.

Probe electronics are encapsulated in the rugged epoxy probe head.

A five conductor cable including the drain or shield wire is used to provide power and ground as well as serial communication with the CS650. The CS650 is intended to communicate with SDI-12 recorders, including Campbell Scientific CR200X-series, CR10X, CR23X, CR800-series, CR1000, CR3000 and CR5000 dataloggers. The orange Rx wire can be used to communicate by means of RS-232 Tx/Rx. The A200 USB-to-Serial Module allows RS-232 serial communication between a computer and the CS650 by means of Campbell Scientific's Device Configuration Utility software, DevConfig.

2. Sensors Specifications

2.1 Dimensions/Weight

	CS650	**CS655**
Rods:	300 mm long 3.2 mm diameter 32 mm spacing	120 mm long 3.2 mm diameter 32 mm spacing
Probe Head:	L 85 mm W 63 mm D 18 mm	L 85 mm W 63 mm D 18 mm
Probe Weight:	280 g	240 g
Cable Weight:	35 g m^{-1}	35 g m^{-1}

2.2 Electrical Specifications

Sensor Output: SDI-12
Serial RS-232

Measurement Time: 3 msec to measure
600 msec to complete SDI-12 command

Power Supply Requirements: 6 VDC – 18 VDC
Must be able to supply 45 mA @ 12 VDC

Current

Active (3 msec): 45 mA typical @ 12 VDC
(80 mA @ 6 VDC, 35 mA @ 18 VDC)

Quiescent: 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 CS650's
s = number of seconds between measurements
(see Figure 2-1)

Maximum Cable Length: 610 m (2000 ft) combined length for 1 – 10 sensors connected to the same datalogger control port

Electromagnetic Compatibility: Œ compliant (EMC compliant performance criteria available upon request)

Meets EN61326 requirements for protection against electrostatic discharge and surge

External RF sources can affect CS650 measurements. CS650 circuitry should be located away from radio transmitter aerials and cables, or measurements ignored during RF transmissions.

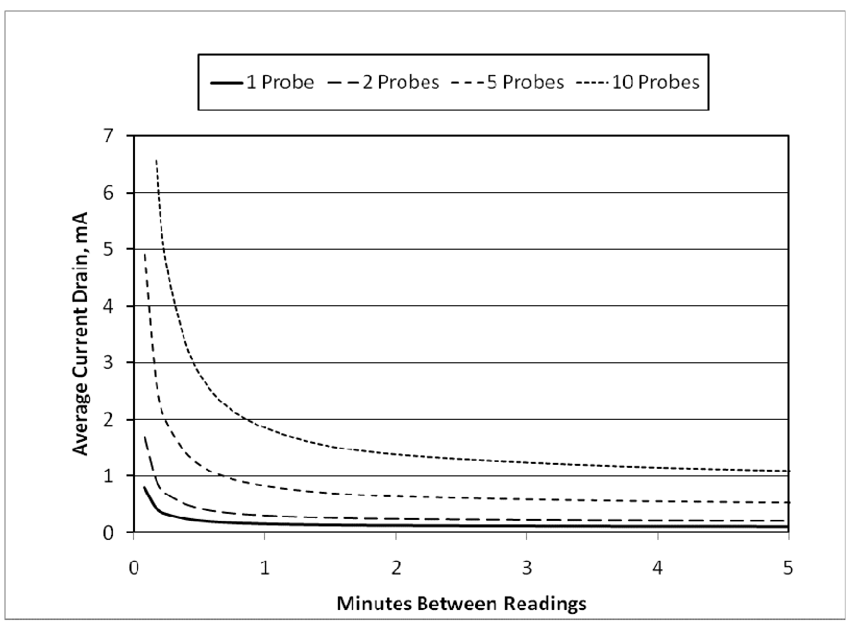


FIGURE 2-1. CS650 and CS655 Average Current Drain

Figure 2-1 shows average current drain for different measurement rates and quantities of CS650 probes. If the time between measurements is five minutes or longer, average current drain may be approximated at 0.15 milliamps per sensor.

2.3 Operational Specifications

	CS650	**CS655**
Relative Dielectric Permittivity		
Range:	1 to 81	1 to 81
Accuracy†:		
1 to 40	±(2% of reading + 0.6) for solution 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	<0.02
Volumetric Water Content using Topp Equation (m^3/m^3)		
Range:	5% to 50%	5% to 50%
Accuracy†:	±3% VWC typical in mineral soils where solution EC ≤3 dS/m	±3% VWC typical in mineral soils where solution EC ≤10 dS/m
Precision‡:	<0.05%	<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)	±(5% of reading + 0.05 dS/m)
Precision‡:	0.5% of BEC	0.5% of BEC

	CS650	**CS655**
Temperature		
Soil Measurement Range:	-10 to + 70°C	-10 to + 70°C
Operational Range:	0 to + 70°C	0 to + 70°C
Accuracy†:	±0.5°C for probe body buried in soil	±0.5°C for probe body buried in soil
Precision‡:	±0.02°C	±0.02°C
Sensing Volume*:	7800 cm^3	3600 cm^3

***Sensing Volume** approximately 7.5 cm radius around each probe 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.

3. Installation

3.1 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 probe rods may be inserted vertically into the soil surface or buried at any orientation to the surface. The probe may be installed 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”) from the rods along their length and 4.5 cm (1.8”) beyond the end of the rods. Consequently, if the probe is buried horizontally closer than 7.5 cm from the soil surface, it will include air above the surface in its measurements and underestimate 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 probe 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 probe body must be in thermal equilibrium with the soil. If the probe is installed vertically with the epoxy probe body above the surface, then the probe body must be shielded from solar radiation and in direct contact with the soil or media of interest.

3.2 Proper Insertion

The method used for probe installation can affect the accuracy of the measurement. The probe rods should be kept as close to parallel as possible when installed to maintain the design wave guide geometry. The probe is more sensitive to permittivity close to the rods so probes inserted in a manner which generates air voids around the rods will have reduced measurement accuracy. In most soils, the soil structure will recover from the disturbance during probe insertion.

In some applications, installation can be improved by using insertion guides or a pilot tool. Campbell Scientific offers the 14383 and 14384 insertion tools. The 14383 is a probe insertion guide which holds the rods parallel during rod insertion. The 14384 pilot tool is inserted into the soil and then removed. This makes proper installation of the Water Content Reflectometer easier in compacted soils.

FIGURE 3-1. 14383 Insertion Guide Tool and 14384 Pilot Rod Tool

4. Wiring

CS650 connections to a datalogger are shown below. Dataloggers are divided into those which are programmed with the CRBasic programming language and those that are programmed with Edlog. CRBasic dataloggers include the CR1000, CR3000, CR5000, CR800-series, and CR200X-series. Compatible Edlog dataloggers include the CR10X, CR23X, and CR510.

4.1 SDI-12 Wiring

Table 4-1 shows the SDI-12 wiring code for the CS650 water content reflectometer. SDI-12 data is transmitted to a CRBasic datalogger odd numbered control port or to any control port of an Edlog datalogger that is capable of SDI-12 communication. See Section 5 for SDI-12 programming examples.

TABLE 4-1. CS650 Wiring Code for SDI-12		
Color	**Function**	**Datalogger Connection**
Green	SDI-12 Data	SDI-12 Input or Control Port
Red	SDI-12 Power	12 Vdc
Black	SDI-12 Reference	G
Clear	Shield	G
Orange	Not Used	G

SDI-12 communication has the advantage that up to ten probes may be given different addresses and share a single control port. Another advantage is that the datalogger programming is much simpler for SDI-12 communication than RS-232.

NOTE The orange Rx wire is only used for RS-232 Tx/Rx communication, and should be grounded when using SDI-12.

4.2 RS-232 Wiring

Table 4-2 shows the wiring code for communicating with a CS650 using RS-232 serial protocol. Device Configuration Utility software uses RS-232 to communicate with a CS650 through the A200 USB-to-Serial Module. See Section 5.1 for details.

RS-232 communication is not recommended for use with Campbell Scientific dataloggers because it requires two control ports per CS650 and the programming is more complicated than for SDI-12 communication.

For RS-232 serial communication with devices other than Campbell Scientific dataloggers, use the wiring information in Table 4-2. Factory default communication settings are 9600 baud, no parity, 1 stop bit, 8 data bits, and no error checking.

See Table 5-2 for a list of serial commands for the CS650.

TABLE 4-2. 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

5. Serial Communication and Datalogger Programming

5.1 A200 and DevConfig

The A200 USB-to-Serial Module allows communication between a CS650 and a PC, allowing sensor settings to be changed through Device Configuration Utility (DevConfig) software.

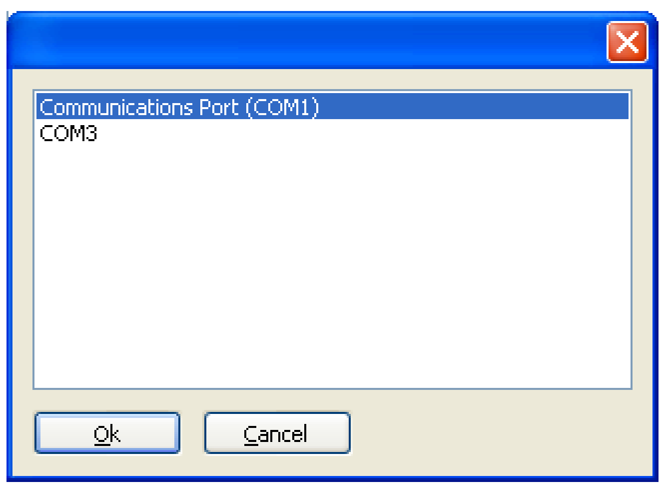
FIGURE 5-1. A200 USB-to-Serial Module

DevConfig may be downloaded from the Campbell Scientific website, www.campbellsci.com/downloads.

Connect the CS650 to the A200 as shown in Table 4-2. Connect the PC to the A200 USB port with the supplied USB cable.

Launch DevConfig and select "CS650 Series" from the Device Type menu on the left. Select 9600 from the Baud Rate drop-down menu.

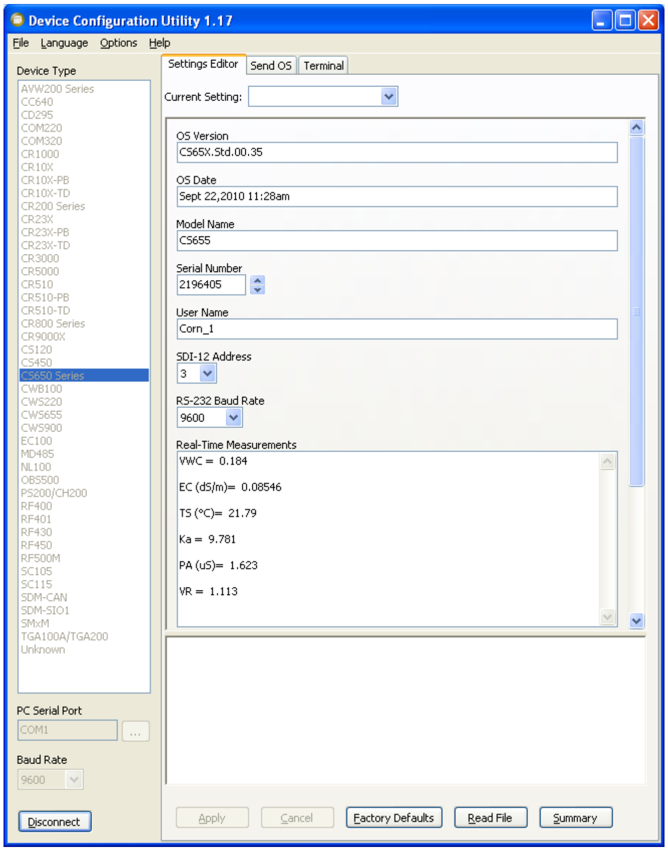
Select the appropriate PC Serial Port from the list of available COM ports shown when the browse button on the lower left is selected:



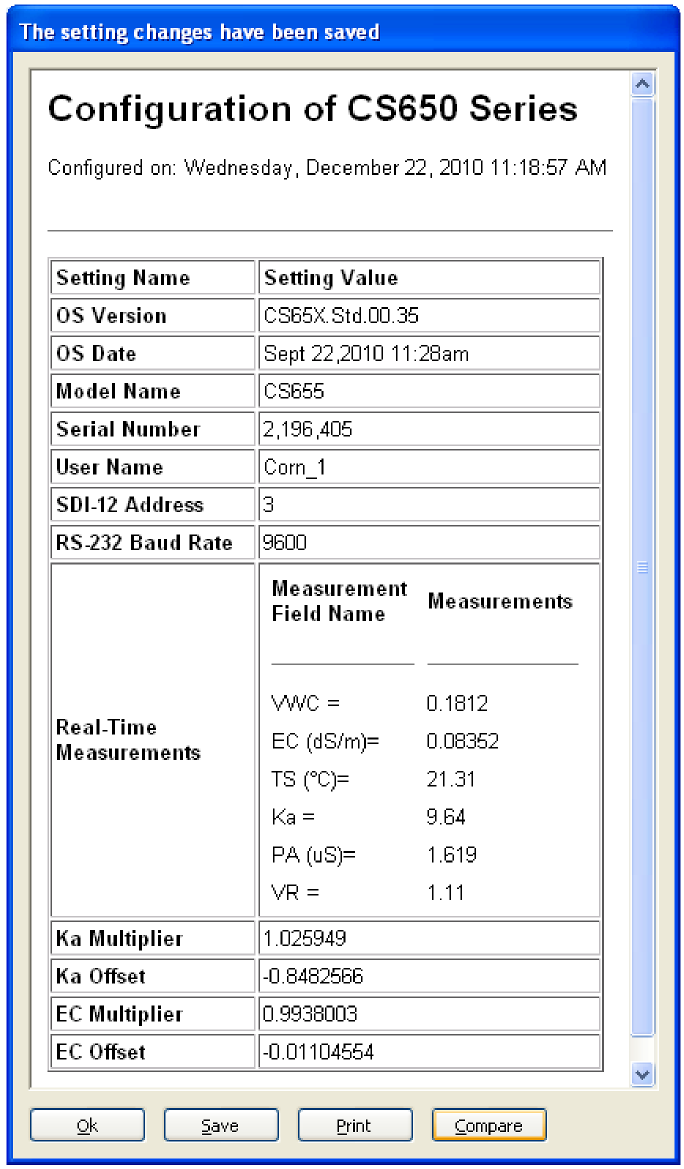
Select Ok and then Connect to begin communication with the CS650.

5.1.1 Settings Editor Tab

The Settings Editor tab shows settings stored in the CS650 firmware. Settings that may be modified include User Name, SDI-12 Address, and RS-232 Baud Rate. Attempts to change any of the other settings will result in a "Commit failed. Unrecognized error condition" error message. DevConfig polls the CS650 every two seconds while connected and the results are displayed in the Real-Time Measurements field. This is useful for verifying probe performance.



After any changes to CS650 settings, select Apply to write the changes to the CS650 firmware. A configuration summary is then shown. The summary may be printed or saved electronically for future reference.

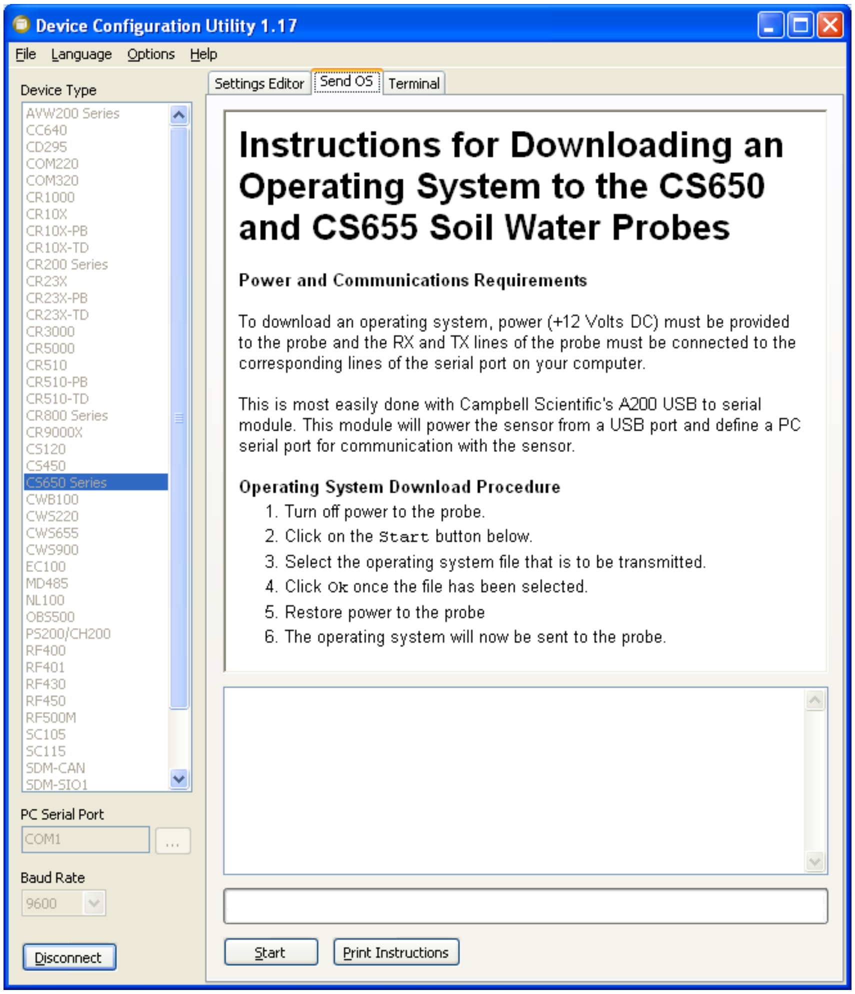


Real-Time Measurements	
Measurement Field Name	**Meaning**
VWC	Volumetric Water Content
EC (dS/m)	Bulk Electrical Conductivity
TS (°C)	Soil Temperature
Ka	Bulk Dielectric Permittivity
PA (μS)	Period Average
VR	Voltage Ratio

5.1.2 Send OS Tab

The Send OS tab is used to update the firmware in the CS650. The firmware is available at www.campbellsci.com/downloads. The file to send will have a filename extension of .a43, such as CS65X.Std.00.36.a43. Sending a new operating system will not affect any of the user-modified settings or probe specific multiplier and offset settings.

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



5.1.3 Terminal Tab

The Terminal tab may be used to send serial commands directly to the CS650. See Table 5-1 for a list of serial interface commands. To send a command from the Terminal tab, left click in the field to get a flashing black cursor, then press <Enter> several times until the CS650> prompt is shown. At the prompt, type in the command then <Enter>.

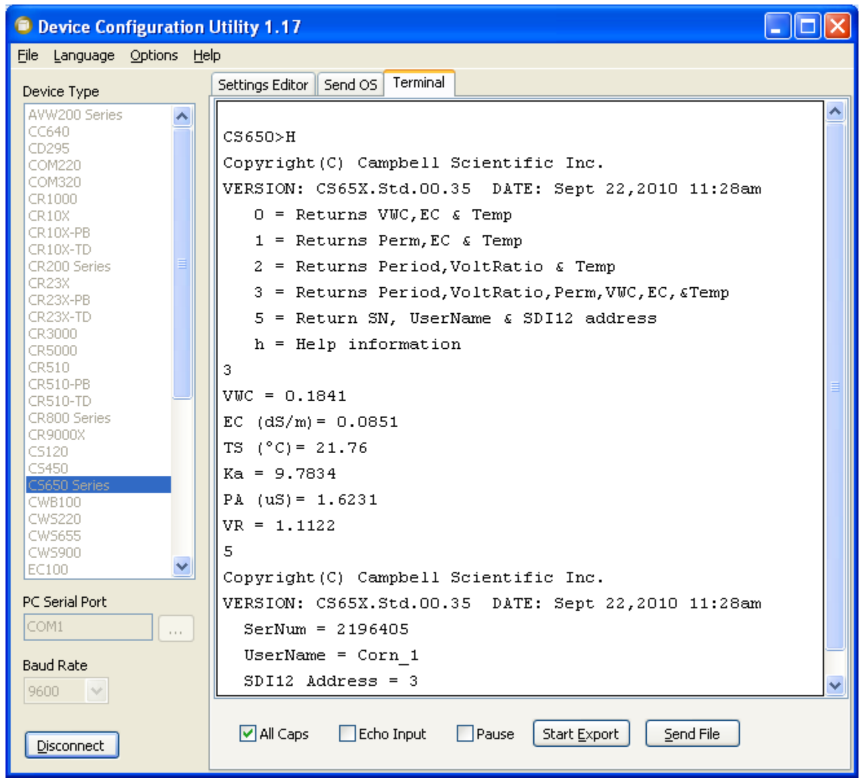


TABLE 5-1. CS650 Terminal Commands		
Command	**Values Returned**	**Units**
0	1) Volumetric Water Content, θ 2) Electrical Conductivity, σ 3) Temperature	m^3/m^3 dS/m °C
1	1) Permittivity, ε 2) Electrical Conductivity, σ 3) Temperature	 dS/m °C
2	1) Period, τ 2) Voltage Ratio, α 3) Temperature	μSec °C
3	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 °C μSec
5	1) Copyright information 2) OS version and Date 3) Product Serial Number 4) Product User Name 5) SDI-12 Address	
H or h	Help Menu	

5.2 SDI-12 Measurements

The CS650 responds to SDI-12 commands M!, M1!, M2!, M3!, ?!, and I!. Table 5-2 shows the values returned for each of these commands. The ?! and I! commands are not used with Edlog dataloggers.

See Section 4.1 for SDI-12 wiring details.

See Appendix B for additional detail concerning SDI-12 sensors, including changing the SDI-12 address in SDI-12 transparent mode.

TABLE 5-2. CS650 SDI-12 Commands

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 °C
aM1!	1) Permittivity, ε 2) Electrical Conductivity, σ 3) Temperature	 dS/m °C
aM2!	1) Period, τ 2) Voltage Ratio, α 3) Temperature	µSec °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 °C µSec
aM4! .. aM9!	No Values Returned	
?!	Returns the SDI-12 Address	
aI!	CampbellSci, OS version, Product Serial Number	

Up to 10 CS650's may be connected to the same datalogger control port as long as each one has a unique SDI-12 address. The CS650 ships with a default SDI-12 address of 0 unless otherwise specified at the time of ordering. The SDI-12 address may be changed through DevConfig software (see Section 5.1) or with a terminal emulator in SDI-12 transparent mode (see Appendix B).

SDI-12 communication is established using the CRBasic instruction SDI12Recorder for CRBasic dataloggers or the Edlog program instruction P105 SDI-12 Recorder. See Appendix B for more detail on SDI-12 communication.

5.2.1 Use of Multiplexers

Multiplexers such as Campbell Scientific's AM16/32B may be used to connect up to 32 CS650 probes to a single control port. When using multiplexers, the simplest configuration is for all probes to have the same SDI-12 address.

When multiplexing CS650 probes, the switched 12V channel should be used so that power to the sensor may be turned off under program control before the multiplexer switches to the next channel.

CAUTION Failure to turn off the switched 12 volt channel before clocking the multiplexer will result in damage to the multiplexer relays.

The proper sequence in the datalogger program for measuring CS650 probes on a multiplexer is:

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

Program examples in Section 5.3 show the commands used in CRBasic and Edlog for this sequence.

5.3 Program Examples

5.3.1 CR1000 with a Single CS650 Probe

This CRBasic example program measures one CS650 probe on a CR1000 every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature. The CS650 has an SDI-12 address of 0. Wiring for this example is shown in Table 5-3.

TABLE 5-3. Wiring for Program Example 1

CR1000	**CS650**
12V	Red
C1	Green
G	Black, Orange, Clear

CRBasic Code Example 1. CR1000 Program to Measure a Single CS650 Probe

```
Dim i
Public CS650(3)
'Assign aliases to the public array
Alias CS650(1)=VWC: Alias CS650(2)=EC: Alias CS650(3)=TSoil
Units VWC = m^3/m^3: Units EC = dS/m: Units TSoil = deg C

DataTable (DatoutCS650,1,-1)
  DataInterval (0,60,Min,2)
  Average (3,CS650(),FP2,False)
EndTable

BeginProg
  Scan (15,Min,0,0)
    'Load array with NAN's to detect bad sensors or readings
    Move (CS650(),3,NAN,1)
    For i = 1 To 3    'Try up to 3 times for valid readings
      SDI12Recorder (CS650(1),1,0,"M!",1.0,0)
      If CS650(1)<>NAN Then ExitFor
    Next i
    CallTable DatoutCS650   'Call Data Table
  NextScan
EndProg
```

5.3.2 CR1000 with 12 CS650 Probes

This CRBasic example program measures 12 CS650 probes on a AM16/32B multiplexer every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature. All probes have an SDI-12 address of 0. Wiring for the example is shown in Table 5-4.

TABLE 5-4. Wiring for Program Example 2

CR1000	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 Channels 1H – 12H	Red
	Low Channels 1L – 12L	Green
	Ground Channels to Left of Low Channels	Black, Orange, Clear

CRBasic Code Example 2. CR1000 Program to Measure 12 CS650 Probes on a AM16/32 Multiplexer

```
Dim LCount
Dim i
Public CS650(12,3)
'Assign aliases to the public array
Alias CS650(1,1)=VWC_1: Alias CS650(1,2)=EC_1
Alias CS650(1,3)=Temp_1: Alias CS650(2,1)=VWC_2
Alias CS650(2,2)=EC_2: Alias CS650(2,3)=Temp_2
Alias CS650(3,1)=VWC_3: Alias CS650(3,2)=EC_3
Alias CS650(3,3)=Temp_3: Alias CS650(4,1)=VWC_4
Alias CS650(4,2)=EC_4: Alias CS650(4,3)=Temp_4
Alias CS650(5,1)=VWC_5: Alias CS650(5,2)=EC_5
Alias CS650(5,3)=Temp_5: Alias CS650(6,1)=VWC_6
Alias CS650(6,2)=EC_6: Alias CS650(6,3)=Temp_6
Alias CS650(7,1)=VWC_7: Alias CS650(7,2)=EC_7
Alias CS650(7,3)=Temp_7: Alias CS650(8,1)=VWC_8
Alias CS650(8,2)=EC_8: Alias CS650(8,3)=Temp_8
Alias CS650(9,1)=VWC_9: Alias CS650(9,2)=EC_9
Alias CS650(9,3)=Temp_9: Alias CS650(10,1)=VWC_10
Alias CS650(10,2)=EC_10: Alias CS650(10,3)=Temp_10
Alias CS650(11,1)=VWC_11: Alias CS650(11,2)=EC_11
Alias CS650(11,3)=Temp_11: Alias CS650(12,1)=VWC_12
Alias CS650(12,2)=EC_12: Alias CS650(12,3)=Temp_12

DataTable (DatoutCS650,1,-1)
   DataInterval (0,60,Min,2)
   Average (36,CS650(),FP2,False)
EndTable

BeginProg
   Scan (15,Min,0,0)
     PortSet(2,1)     'Turn AM16/32 Multiplexer On
     Delay(0,150,mSec)
     LCount=1
     'Load array with NAN's to detect bad sensors or readings
     Move (CS650(),36,NAN,1)
     SubScan(0,uSec,12)
        PulsePort(3,10000)  'Switch to next AM16/32 channel
        SW12 (1 )           'Apply power to CS650
        For i = 1 To 3      'Try up to 3 times for valid readings
          SDI12Recorder (CS650(LCount,1),1,0,"M!",1.0,0)
          If CS650(LCount,1)<>NAN Then ExitFor
        Next i
        LCount=LCount+1
        SW12 (0)'Remove power from CS650
      NextSubScan
     PortSet(2,0) 'Turn AM16/32 Multiplexer Off
     CallTable DatoutCS650    'Call Data Table
   NextScan
EndProg
```

5.3.3 CR10X with a Single CS650 Probe

This Edlog example program measures one CS650 probe on a CR10X every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature. The CS650 has an SDI-12 address of 0. Wiring for the example is shown in Table 5-5.

TABLE 5-5. Wiring For Program Example 3

CR10X	CS650
12V	Red
C1	Green
G	Black, Orange, Clear

Edlog Code Example 3. CR10X Program to Measure a Single CS650 Probe

```
;{CR10X}
;
*Table 1 Program
  01: 900       Execution Interval (seconds)

;Overwrite previous reading with -99999 for error flagging
     1:  Scaling Array (A*Loc+B) (P53)
      1: 1        Start Loc [ VWC       ]
      2: 0        A1
      3: -99999   B1
      4: 0        A2
      5: -99999   B2
      6: 0        A3
      7: -99999   B3
      8: 0.0      A4
      9: 0.0      B4

2:  Beginning of Loop (P87) ;Try up to 3 times for valid
readings
 1: 0        Delay
 2: 3        Loop Count

     3:  SDI-12 Recorder (P105)
      1: 0        SDI-12 Address
      2: 0        Start Measurement (aM!)
      3: 1        Port
      4: 1        Loc [ VWC       ]
      5: 1.0      Multiplier
      6: 0.0      Offset
```

```
      4:  If (X<=>F) (P89)
       1: 1        X Loc [ VWC       ]
       2: 3        >=
       3: -99998   F
       4: 31       Exit Loop if True

5:  End (P95)

6:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)

7:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 60       Array ID

8:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

9:  Average (P71)
 1: 3        Reps
 2: 1        Loc [ VWC       ]
```

5.3.4 CR10X with 12 CS650 Probes

This Edlog example program measures 12 CS650 probes on a AM16/32B multiplexer every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature. All probes are addressed with SDI-12 address of 0. Wiring for the example is shown in Table 5-6.

TABLE 5-6. Wiring For Program Example 4

CR10X	AM16/32B (2x32 mode)	CS650
12V	12V	
G	GND	
C2	RES	
C3	CLK	
SW 12V	COM ODD H	
C1	COM ODD L	
G	COM Ground	
C8 to SW12V CTRL		
	High Channels 1H – 12H	Red
	Low Channels 1L – 12L	Green
	Ground Channels to Left of Low Channels	Black, Orange, Clear

Edlog Code Example 4. CR10X Program to Measure 12 CS650 Probes on a AM16/32B Multiplexer

```
;{CR10X}
;
*Table 1 Program
  01: 30        Execution Interval (seconds)

;Overwrite previous reading with -99999 for error flagging

1:  Beginning of Loop (P87)
 1: 0        Delay
 2: 36       Loop Count

     2:  Z=F x 10^n (P30)
      1: -99999   F
      2: 00       n, Exponent of 10
      3: 4     -- Z Loc [ VWC_1     ]

3:  End (P95)

;Turn on AM16/32B multiplexer
4:  Do (P86)
 1: 42       Set Port 2 High

5:  Beginning of Loop (P87)
 1: 0        Delay
 2: 12       Loop Count

     6:  Do (P86) ;Advance to next AM16/32 channel
      1: 73       Pulse Port 3

     7:  Do (P86) ;                  Apply power to CS650
      1: 48       Set Port 8 High

     8:  Beginning of Loop (P87) ;  Try up to 3 times for valid
readings
      1: 0        Delay
      2: 3        Loop Count

          9:  SDI-12 Recorder (P105)
           1: 3        SDI-12 Address
           2: 0        Start Measurement (aM!)
           3: 1        Port
           4: 1        Loc [ SDI_1     ]
           5: 1.0      Multiplier
           6: 0.0      Offset
```

```
          10:  If (X<=>F) (P89)
           1: 1        X Loc [ SDI_1     ]
           2: 3        >=
           3: -99998   F
           4: 31       Exit Loop if True

     11:  End (P95)

;Move readings to proper input locations
     12:  Block Move (P54)
      1: 3        No. of Values
      2: 1        First Source Loc [ SDI_1     ]
      3: 1        Source Step
      4: 4     -- First Destination Loc [ VWC_1     ]
      5: 12       Destination Step

     13:  Do (P86) ;Remove power from CS650
      1: 58       Set Port 8 Low

14:  End (P95)

;Turn off AM16/32B multiplexer
15:  Do (P86)
 1: 52       Set Port 2 Low

16:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)

17:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 60       Array ID

18:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

19:  Average (P71)
 1: 36       Reps
 2: 4        Loc [ VWC_1     ]
```

5.3.5 CR200X with 3 CS650 Probes

This CRBasic example program measures 3 CS650 probe on a CR200X every 15 minutes, storing hourly averages of volumetric water content, electrical conductivity, and soil temperature. The CS650's have SDI-12 addresses of 0, 1, and 2. Wiring for the example is shown in Table 5-7.

TABLE 5-7. Wiring For Program Example 5

CR200X	CS650
SW Battery	Red
C1/SDI-12	Green
G channels	Black, Orange, Clear

CRBasic Code Example 5. CR200X Program to Measure 3 CS650 Probes

```
Dim i
Public CS650(9)
'Assign aliases to the public array
Alias CS650(1)=VWC_1: Alias CS650(2)=EC_1
Alias CS650(3)=TSoil_1: Alias CS650(4)=VWC_2
Alias CS650(5)=EC_2: Alias CS650(6)=TSoil_2
Alias CS650(7)=VWC_3: Alias CS650(8)=EC_3
Alias CS650(9)=TSoil_3

DataTable (CS650,1,-1)
  DataInterval (0,60,Min)
  Average (9,CS650(),False)
EndTable

BeginProg
  Scan (15,Min)
    'Load array with NAN's to detect bad sensors or readings
    For i = 1 To 9
      CS650(i)=NAN
    Next i
    SWBatt (1 )       'Apply power to CS650's

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

    'CS650 #2
      SDI12Recorder (CS650(4),"1M!",1,0)

    'CS650 #3
      SDI12Recorder (CS650(7),"2M!",1,0)

    SWBatt (0 )       'Remove power from CS650's
    CallTable CS650   'Call Data Table
  NextScan
EndProg
```

6. The Water Content Reflectometer Method for Measuring Volumetric Water Content

6.1 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 probe 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.

6.2 The 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 3rd 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

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

It has been shown in numerous research efforts that this equation works well in most mineral soils, so a soil specific calibration of the CS650 probe is usually not necessary. If a soil specific calibration is desired, the user can generate an equation relating K_a to θ_v following the methods described in Section 7.

6.3 Electrical Conductivity

6.3.1 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 probe 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. Soil solution electrical conductivity, $\sigma_{solution}$ can be determined in the laboratory using extraction methods to separate the solution from the solid and then measuring the electrical conductivity of the extracted solution.

The relationship between solution and bulk electrical conductivity can be described by (Rhoades et al., 1976)

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

with σ_{bulk} being the electrical conductivity of the bulk soil; $\sigma_{solution}$, the soil solution; σ_{solid}, the solid constituents; θ_v, the volumetric water content; andT, 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 firmware corrects the oscillation frequency for the effects of $\sigma_{solution}$ 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 probe will return 99999 for dielectric permittivity and volumetric water content. The measured period average and voltage ratio values will continue to be reported even if the bulk EC is outside the operational range of the probe.

6.3.2 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, EC readings may be converted to a standard temperature, such as 25 °C using the following equation:

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

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).

6.4 Error Sources in Water Content Reflectometer Measurement

6.4.1 Probe-to-Probe Variability Error

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

6.4.2 Insertion Error

The method used for probe insertion can affect the accuracy of the measurement. The probe 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. Probes inserted in a manner that generates air voids around the rods will indicate lower water content than actual. In some applications, installation can be improved by using insertion guides or a pilot tool. Campbell Scientific offers the 14383 and 14384 insertion tools.

6.5 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 probe electronics and the effect of temperature on the dielectric permittivity of the soil.

The effect of temperature on probe electronics is minimal with period average readings varying by less than 0.5% of the 20 °C reading over the range of 10 °C to 30 °C and less than 2% of the 20 °C reading over the range of -10 °C 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 will 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:

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

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.

6.5.1 Accurate Soil Temperature Measurement

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

7. Water Content Reflectometer User-Calibration

7.1 Need for Soil Specific Calibration Equation

While the Topp equation has been determined to work well in a wide range of mineral soils, there are soils for which a user-derived calibration will optimize 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 probe is expected to measure.

7.2 The User-Derived Calibration Equation

The relationship between soil permittivity and volumetric water content may be described by a quadratic equation or a 3rd order polynomial. In many applications, a linear equation similar to Ledieu et al (1986) gives required accuracy.

Quadratic form:

$$\theta_v(K_a) = C_0 + C_1{*}K_a + C_2{*}K_a^2$$

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

3rd degree polynomial form:

$$\theta_v(K_a) = C_0 + C_1{*}K_a + C_2{*}K_a^2 + C_3{*}K_a^3$$

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

Linear form:

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

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 can be enough to derive a linear calibration. A minimum of three data points are needed for a quadratic calibration. With three evenly spaced water contents covering the expected range, the middle water content data point will indicate whether a linear or polynomial calibration equation is needed.

A minimum of four data points are required for derivation of a 3rd degree polynomial. Data points should be spaced as evenly as practical over the expected range of water content and include the wettest and driest expected values.

7.3 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, the probe response to changing water content can be described by a linear or polynomial function as described in Section 7.2

Required equipment:

1. CS650 connected to datalogger programmed to measure permittivity
2. Cylindrical sampling devices to determine sample volume for bulk density, e.g. copper tubing of diameter ≥ 1” and length about 2”
3. Containers and scale to measure soil sample mass
4. Oven to dry samples (microwave oven can also be used)

The calibration coefficients are derived from a curve fit of known water content and probe 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 will determine whether the function is a quadratic or 3rd order polynomial. Accuracy requirements may require additional data sets. Consider the expected range of soil water content and include data sets from the highest and lowest expected water contents.

The measurement sensitive volume around the probe rods must be completely occupied by the calibration soil. Only soil should be in the region within 10 cm (4 inches) of the rod surface. The probe rods can be buried in a tray of soil that is dry or nearly dry. The soil will be homogeneous around the probe rods if it is poured around the rods while dry. Also, a 20 cm diameter PVC pipe with length about 35 cm can be closed at one end and used as the container.

It is important that the bulk density of the soil used for calibration be similar to the bulk density of the undisturbed soil. Using dry soil without compaction will give a typical bulk density, 1.1 - 1.4 g cm^{-3}. This is especially important when bulk density is greater than 1.55 g cm^{-3}. Compaction of the calibration soil to similar bulk density at the field site is necessary for an accurate calibration.

The typically used method for packing a container of soil to uniform bulk density is to roughly separate the soil into three or more equal portions and add one portion to the container with compaction. Evenly place the first loose soil layer in the bottom of the container. Compact by tamping the surface to a level in the container that is correct for the target bulk density. Repeat for the remaining layers. Prior to placing successive layers, scarify (loosen) the top of the existing compacted layer.

The container to hold the soil during calibration should be non-metal and large enough that the rods of the probe are no closer than about 10 cm from any container surface.

Pack the container as uniformly as possible in bulk density with relatively dry soil (volumetric water content <10%).

Probe rods can be buried in a tray or inserted into a column. When using a column, insert the rods carefully through surface until rods are completely surrounded by soil. Movement of rods from side-to-side during insertion can form air voids around rod surface and lead to measurement error.

Collect the probe permittivity output. Repeat previous step and this step 3 or 4 times.

Determine volumetric water content by subsampling soil column after removing probe or using mass of column. If subsampling is used, remove soil from column and remix with samples used for water content measurement. Repack column.

Water can then be added to the top of the container. It must be allowed to equilibrate. Cover the container during equilibration to prevent evaporation. The time required for equilibration depends on the amount of water added and the hydraulic properties of the soil. Equilibration can be verified by frequently observing the CS650 permittivity output. When permittivity is constant, equilibration is achieved. Collect a set of calibration data values and repeat the water addition procedure again if needed.

With soil at equilibrium, record the CS650 permittivity.

Take subsamples of the soil using containers of known volume. This is necessary for measurement of bulk density. Copper tubing of diameter ≥ 1" and length about 2" works well. The tubes can be pressed into the soil surface.

It is good to take replicate samples. Three carefully handled samples will provide good results.

The sample tubes should be pushed evenly into the soil. Remove the tube and sample and gently trim the ends of excess soil. Remove excess soil from outside of tube.

Remove all the soil from tube to a tray or container of known mass that can be put in oven or microwave. Weigh and record the wet soil mass.

Water is removed from the sample by heating with oven or microwave. Oven drying requires 24 hours at 105C. 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.

Gravimetric water content is calculated after the container mass is accounted for.

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

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

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

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

7.4 Collecting Field Data for Calibration

Required equipment

1. CS650 connected to datalogger programmed to measure probe permittivity

2. Cylindrical sampling devices to determine sample volume for bulk density, e.g. copper tubing of diameter ≥ 1” and length about 2”

3. Containers and scale to measure soil sample mass

4. Oven to dry samples (microwave oven can also be used)

Data needed for CS650 calibration are the CS650 permittivity output and an independently determined volumetric water content. From this data, the probe response to changing water content can be described by a function as described in Section 7.2.

The calibration coefficients are derived from a curve fit of known water content and probe 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 will determine whether the function is a quadratic or 3^{rd} order polynomial. Accuracy requirements may require 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 probe is to be used will provide the best on-site soil-specific calibration. However, intentionally changing water content in soil profiles can be difficult.

A vertical face of soil can be formed with a shovel. If the CS650 is to be used within about 0.5 meters of the surface, the probe can be inserted into the face and water added to the surface with percolation. After adding water, monitor the CS650 permittivity to determine if the soil around the rods is at equilibrium.

With soil at equilibrium, record the CS650 permittivity.

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 3 times into the soil recording the permittivitys following each insertion and using the average.

Remove the CS650 and take core samples of the soil where the probe rods were inserted. This is necessary for measurement of bulk density. Copper tubing of diameter ≥ 1” and length about 2” works well. The tubes can be pressed into the soil surface.

It is good to take replicate samples at locations around the soil surface. Three carefully handled samples will provide good results.

The sample tubes should be pushed evenly into the soil surface. Remove the tube and sample and gently trim the ends of excess soil. Remove excess soil from outside of tube.

Remove all the soil from tube to a tray or container of known mass that can be put in oven or microwave. Weigh and record the wet soil mass. 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.

Water is removed from the sample by heating with 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.

Gravimetric water content is calculated after the container mass is accounted for.

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

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

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

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

7.5 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

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

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 will hold 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 above.

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

$$\theta_v = \theta_g * \rho_{bulk} .$$

8. Maintenance

The CS650 does not require periodic maintenance.

9. Troubleshooting

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 (P105 for Edlog dataloggers) to datalogger program Check logic of conditional statement that triggers readings
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	Change probe address or modify program so that they match

Symptom	Possible Cause	Solution
(*or all values read NAN if the program examples in this manual are followed)	CS650 green wire not attached to SDI port specified in datalogger program	Connect wire to correct control port or modify program to match wiring
	CS650 not being powered	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.
	SW12V channel not turning on	If using SW 12V on a CR10X, ensure that a wire connects a control port to SW12V CTRL and the program sets that control port high.
VWC reading is 9999999	Soil bulk permittivity is outside probe's operational range	Modify program to collect permittivity value and try soil specific calibration
EC reading is 9999999	Soil bulk electrical conductivity is outside probe's operational range	If using CS650, try CS655
Readings erratic, including NAN's and 9999999's	Multiple probes with same SDI-12 address sharing same control port	Give probes unique addresses or put on separate control ports

10. References

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Appendix A. 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, 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:

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

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 B. SDI-12 Sensor Support

B.1 SDI-12 Command Basics

SDI-12 commands have three components:

Sensor address (a) – a single character, and is the first character of the command. CS650 sensors are usually assigned a default address of zero unless option –VS is selected at the time of ordering. Sensors with the –VS option are addressed with the last digit of the probe's serial number. This allows for multiple CS650's to be connected to a single control port without requiring the user to change the SDI-12 addresses from zero.

Command body (e.g., M1) – an upper case letter (the "command") followed by alphanumeric qualifiers.

Command termination (!) – an exclamation mark.

An active sensor responds to each command. Responses have several standard forms and terminate with <CR><LF> (carriage return – line feed).

SDI-12 commands supported by the CS650 are listed in Table B.1-1. Continuous and concurrent measurements are not supported.

TABLE B.1-1. CS650 SDI-12 Command and Response Set

Name	Command	Response
Acknowledge Active	a!	a<CR><LF>
Send Identification	aI!	allccccccccmmmmmmvvvxxx...xx<CR><LF>
Change Address	aAb!	b<CR><LF>
Address Query	?!	a<CR><LF>
Start Measurement	aM!	atttn<CR><LF>
Send Data	aD0! aD1!	a<values><CR><LF> a<values><CR><LF>
Additional Measurements	aM1! aM2! aM3!	atttn<CR><LF> atttn<CR><LF> atttn<CR><LF>

Address Query Command (?!)

Command *?!* requests the address of the connected sensor. The sensor replies to the query with the address, *a*.

Change Address Command (aAb!)

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.

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.

An example of a response from the aI! command is:

313CampbellCS65X 000Std.00.35=2196405 <CR><LF>

where:

Address = 3

SDI-12 version =1.3

Manufacturer = Campbell

Sensor model = CS65X

OS version = 000Std.00.35

Sensor serial number = 2196405

Start Measurement Commands (aM!)

A measurement is initiated with M! commands. The response to each command has the form atttnn, where

a = sensor address

ttt = time, in seconds, until measurement data are available

nn = the number of values to be returned when one or more subsequent *D!* commands are issued.

Start Measurement Command (aMv!)

Qualifier *v* is a variable between 1 and 3 that requests variant data. Variants include different subsets of the CS650 probe output:

M0! Volumetric Water Content (θ), Bulk Electrical Conductivity (σ), Temperature (°C)

M1! Permittivity (ε), Bulk Electrical Conductivity (σ), Temperature (°C)

M2! Period (τ), Voltage Ratio (α), Temperature (°C)

M3! Volumetric Water Content (θ), Bulk Electrical Conductivity (σ), Temperature (°C), Permittivity (ε), Period (τ), Voltage Ratio (α)

Aborting a Measurement Command

A measurement command (*M!*) is aborted when any other valid command is sent to the sensor.

Send Data Command (aDv!)

This command requests data from the sensor. It is normally issued automatically by the datalogger after measurement commands *aMv!* In transparent mode, the user asserts this command to obtain data. If the expected number of data values are not returned in response to a *aD0!* command, the data logger issues *aD1!* The limiting constraint is that the total number of characters that can be returned to a *aD0!* command is 35 characters. If the number of characters exceed the limit, the remainder of the response are obtained with the subsequent *aD1!* command.

B.2 Changing the SDI-12 Address Using Terminal Emulator and a Datalogger

Up to ten CS650's or other SDI-12 sensors can be connected to a single datalogger control port. Each SDI-12 device on the same control port must have a unique SDI-12 address. The CS650 supports addresses of 0-9, a-z, and A-Z.

The factory-set SDI-12 address for the CS650 is 0 when the probe is ordered with the –DS option or the last digit of its serial number when ordered with the –VS option. The CS650 SDI-12 address is changed by issuing the aAb! command where *a* is the current address and *b* is the new address. The current address can be found by issuing the ?! command.

The easiest way to change the address on a CS650 sensor is with the Device Configuration Utility and a A200 Sensor to PC Interface as described in Section 5.1. However if a A200 is not available, it is possible to change the address by connecting a single CS650 to a SDI-12 compatible control port on a datalogger and utilizing SDI-12 transparent mode to send commands directly to the sensor.

B.2.1 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. Datalogger security may need to be unlocked before transparent mode can be activated.

Transparent mode is entered while the PC is in telecommunications with the datalogger through a terminal emulator program. It is easily accessed through Campbell Scientific datalogger support software, but is also accessible with terminal emulator programs such as Windows Hyperterminal. Datalogger keyboards and displays cannot be used.

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

The following examples show how to use LoggerNet software to enter transparent mode and change the SDI-12 address of a CS650 sensor. The same steps are used to enter transparent mode with PC200W and PC400 software after accessing the terminal emulator as previously described.

B.2.2 CR200(X) Series Datalogger Example

1. Connect a single CS650 to the datalogger as follows:

    - Green to Control Port C1/SDI12
    - Black, Orange, Clear to G
    - Red to Battery +

2. In the LoggerNet Connect screen navigate to the Datalogger menu and select Terminal Emulator.   The “Terminal Emulator” window will open. In the Select Device menu, located in the lower left-hand side of the window, select the CR200Series station.

3. Click on the Open Terminal button.

4. Press the <enter> key until the datalogger responds with the “**CR2XX>**” prompt.   At the “**CR2XX>**” prompt, make sure the All Caps Mode box is checked and enter the command **SDI12** <enter>. The response “SDI12>” indicates that the CS650 is ready to accept SDI-12 commands.

5. To query the CS650 for its current SDI-12 address, key in ?! <enter> and the CS650 will respond with its SDI-12 address. If no characters are typed within 60 seconds, then the mode is exited. In that case, simply enter the command SDI12 again and press <enter>.

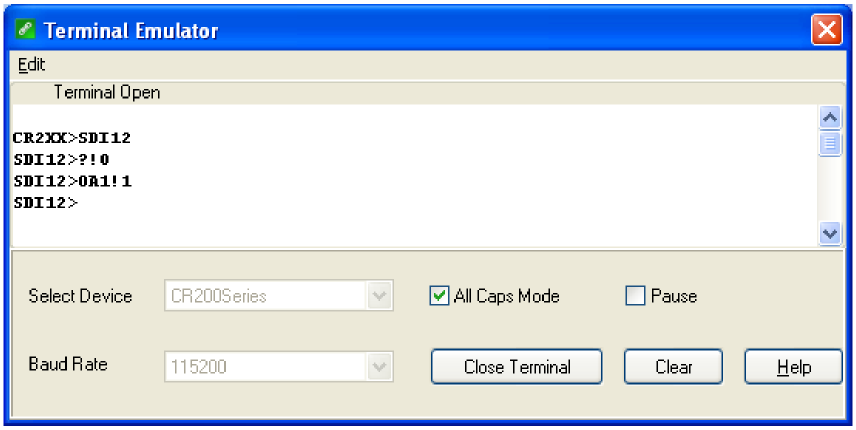

FIGURE B.2-1. SDI-12 Transparent Mode on CR200(X) Series Datalogger using Control Port C1/SDI12 and Changing SDI-12 Address from 0 to 1

6. To change the SDI-12 address, key in **aAb!<enter>** where *a* is the current address from the above step and *b* is the new address. The CS650 will change its address and the datalogger will respond with the new

B.2.3 CR1000 Datalogger Example

1. Connect a single CS650 to the datalogger as follows:

   - Green to Control Port C1
   - Black, Orange, Clear to G
   - Red to 12V

2. In the LoggerNet Connect screen navigate to the Datalogger menu and select Terminal Emulator. The "Terminal Emulator" window will open. In the Select Device menu, located in the lower left-hand side of the window, select the CR1000 station.

3. Click on the Open Terminal button.

4. Press the <enter> key until the datalogger responds with the "**`CR1000>`**" prompt. At the "**`CR1000>`**" prompt, make sure the All Caps Mode box is checked and enter the command **`SDI12`** <enter>. At the "Enter Cx Port 1, 3, 5, or 7" prompt, key in the control port number where the CS650 green lead is connected and <enter>. The response "Entering SDI12 Terminal" indicates that the CS650 is ready to accept SDI-12 commands.

5. To query the CS650 for its current SDI-12 address, key in ?! <enter> and the CS650 will respond with its SDI-12 address. If no characters are typed within 60 seconds, then the mode is exited. In that case, simply enter the command SDI12 again, press <enter>, and key in the correct control port number when prompted.

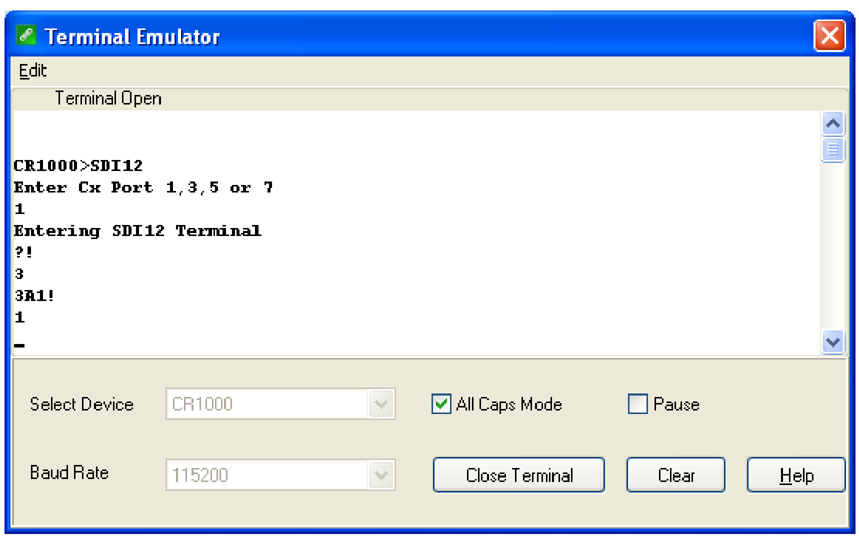

FIGURE B.2-2. SDI-12 Transparent Mode on CR1000 Datalogger using Control Port 1 and Changing SD1-12 Address from 3 to 1.

6. To change the SDI-12 address, key in **`aAb!<enter>`** where *a* is the current address from the above step and *b* is the new address. The CS650 will change its address and the datalogger will respond with the new address. To exit SDI-12 transparent mode, press the Esc key or wait for the 60 second timeout, then select the Close Terminal button.

B.2.4 CR10X Datalogger Example

1. Connect a single CS650 to the datalogger as follows:

   - Green to Control Port C1
   - Black, Orange, Clear to G
   - Red to 12V

2. Download a datalogger program that contains the SDI-12 Recorder (P105) instruction with valid entries for each parameter. Make sure that parameter 3 of the P105 instruction matches the control port number where the green wire is connected.

3. In the LoggerNet Connect screen navigate to the Datalogger menu and select Terminal Emulator. The “Terminal Emulator” window will open. In the Select Device menu, located in the lower left-hand side of the window, select the CR10X station.

4. Click on the Open Terminal button.

5. Press the <enter> key until the datalogger responds with the “*” prompt.

6. To activate the SDI-12 Transparent Mode on Control Port *p*, enter *p*X <enter>. For this example key in 1X <enter>. The datalogger will respond with “**`entering SDI-12`**”. If any invalid SDI-12 command is issued, the datalogger will exit the SDI-12 Transparent Mode.

7. To query the CS650 for its current SDI-12 address, enter the command ?!. The CS650 will respond with the current SDI-12 address.

8. To change the SDI-12 address, enter the command *a*A*b*!; where *a* is the current address from the above step and *b* is the new address. The CS650 will change its address and the datalogger will exit the SDI-12 Transparent Mode.

9. Activate the SDI-12 Transparent Mode on Control Port 1 again by entering 1X <enter>. Verify the new SDI-12 address by entering the ?! command. The CS650 will respond with the new address.

10. To exit the SDI-12 Transparent Mode, enter *.

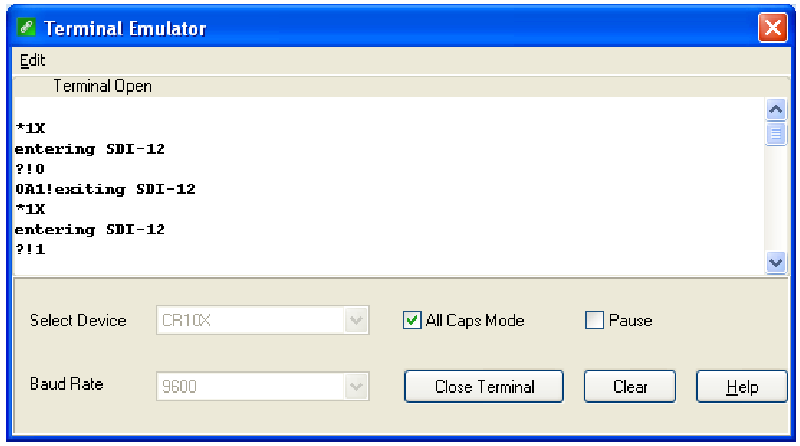

FIGURE B.2-3. SDI-12 Transparent Mode on CR10X Datalogger using Control Port 1 and Changing SDI-12 Address from 0 to 1

B.2.5 CR10X-PB Table-Based Datalogger Example

1. Connect a single CS650 to the datalogger as follows:

   - Green to Control Port C1
   - Black, Orange, Clear to G
   - Red to 12V

2. Download a datalogger program that contains the SDI-12 Recorder (P105) instruction with valid entries for each parameter. Make sure that parameter 3 of the P105 instruction matches the control port number where the green wire is connected.

3. In the LoggerNet Connect screen navigate to the Datalogger menu and select Terminal Emulator.   The "Terminal Emulator" window will open. In the Select Device menu, located in the lower left-hand side of the window, select the CR10XTD or CR10XPB station.

4. Click on the Open Terminal button.

5. Press the <enter> key until the datalogger responds with the ">" prompt.

6. To activate the SDI-12 Transparent Mode on Control Port *p*, enter **`*8`**. The TD datalogger will respond with a "." prompt. At the "." prompt enter **`#`**. The TD datalogger will respond with **`150000`**. Finally, enter *p* (Control Port *p*) and press the <enter> key. For this example, *p* = 1. The TD datalogger will respond with "**`entering SDI-12`**".   If any invalid SDI-12 command is issued, the datalogger will exit the SDI-12 Transparent Mode.

7. To query the CS650 for its current SDI-12 address, enter the command ?!. The CS650 will respond with the current SDI-12 address.

8. To change the SDI-12 address, enter the command *a*A*b*!; where *a* is the current address from the above step and *b* is the new address. The CS650 will change its address and the datalogger will exit the SDI-12 Transparent Mode.

9. Activate the SDI-12 Transparent Mode on Control Port 1 again by entering *8#1 <enter>. Verify the new SDI-12 address by entering the ?! command. The CS650 will respond with the new address.

10. To exit the SDI-12 Transparent Mode, type in ***0**.

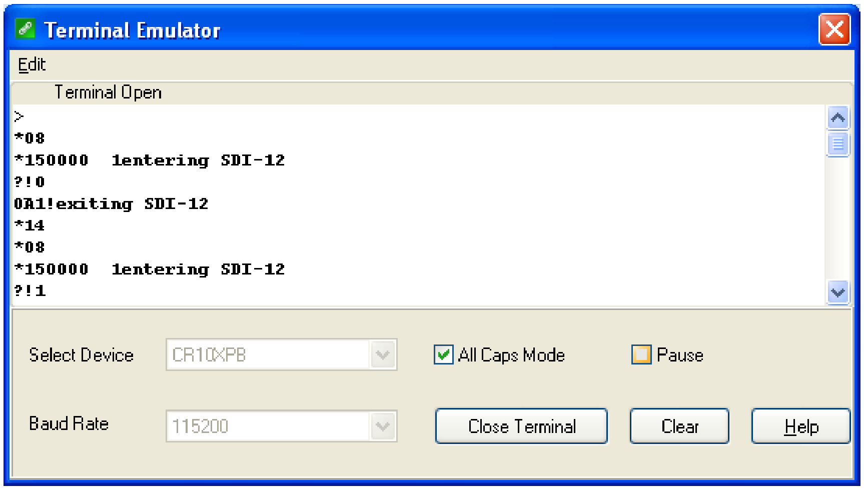

FIGURE B.2-4. SDI-12 Transparent Mode on CR10X-PB Table Based Datalogger using Control Port 1 and Changing SDI-12 Address from 0 to 1

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