IMPORTANT – Please Read

Software requirements for CS616 datalogger instruction 138

PC208W Datalogger Support Software

- PC208W support of CS616 Instruction 138 requires replacement of some PC208W files

The datalogger instruction for the CS616, P138, is a new instruction. The instruction was developed after the release of PC208W version 3.3. Campbell Scientific will not release another version of PC208W but instead will offer the next generation datalogger support software which is LoggerNet. All versions of LoggerNet support instruction 138.

Datalogger instructions for period averaging (P27) can also be used with the CS616. However, Instruction 138 is preferred because it significantly reduces current consumption, measurement time and radiated emissions.

One method to support instruction 138 is to upgrade from PC208W to LoggerNet. If upgrading to LoggerNet does not meet your requirements, follow these steps to upgrade PC208W to version 3.3. You must have PC208W version 3.0 or later to complete this upgrade.

1. Go to Campbell Scientific website http://www.campbellsci.com/resource.html.
2. In section "Product Upgrades", click on link 3.3 to link to the patch for PC208W/P.
3. Follow instructions for On-line Upgrades. An email will be sent to you with a link to the required files for the patch. The patch will upgrade PC208W to version 3.3.
4. Next, download file CS616.exe from our ftp site, ftp://ftp.campbellsci.com/pub/outgoing/files/ to a location of your choice. Open the self-extracting file CS616.exe. The default directory is C:\PC208W\BIN. Select a different location using Browse button if needed. Use button Unzip to overwrite existing files with new files that support PC208W.
5. Follow instructions below to upgrade Datalogger Operating System.

Datalogger Operating Systems

- Use of CS616 instruction 138 requires recent datalogger operating system

The following table lists the datalogger operating systems required for support of instruction 138. To determine which operating system is presently installed in a datalogger, use the *B mode. See datalogger manual for description.

---------- Continued on back of page ----------

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Campbell Scientific Datalogger	Required Operating System Version --Listed version or later--
CR510	1.9
CR10X	1.16
CR23X	1.13

Campbell Scientific datalogger operating systems are easily downloaded from our website page, www.campbellsci.com/resource.html. Go to section Product Upgrades and click on the link for the appropriate datalogger.

If you have questions about this process, please contact us through our website, or, in the USA, call 435/753-2342.

IMPORTANT – Please Read

CS616 AND CS625 WATER CONTENT REFLECTOMETERS
INSTRUCTION MANUAL

REVISION: 4/03

Warranty and Assistance

The **CS616 AND CS625 WATER CONTENT REFLECTOMETERS** are warranted by CAMPBELL SCIENTIFIC, INC. to be free from defects in materials and workmanship under normal use and service for twelve (12) months from date of shipment unless specified otherwise. Batteries have no warranty. CAMPBELL SCIENTIFIC, INC.'s obligation under this warranty is limited to repairing or replacing (at CAMPBELL SCIENTIFIC, INC.'s option) defective products. The customer shall assume all costs of removing, reinstalling, and shipping defective products to CAMPBELL SCIENTIFIC, INC. CAMPBELL SCIENTIFIC, INC. will return such products by surface carrier prepaid. This warranty shall not apply to any CAMPBELL SCIENTIFIC, INC. products which have been subjected to modification, misuse, neglect, accidents of nature, or shipping damage. This warranty is in lieu of all other warranties, expressed or implied, including warranties of merchantability or fitness for a particular purpose. CAMPBELL SCIENTIFIC, INC. is not liable for special, indirect, incidental, or consequential damages.

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CAMPBELL SCIENTIFIC, INC.
RMA#_____
815 West 1800 North
Logan, Utah 84321-1784

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Non-warranty products returned for repair should be accompanied by a purchase order to cover the repair.

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CS616 and CS625 Table of Contents

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CS616 and CS625 Water Content Reflectometers

1. General Description

The CS616 Water Content Reflectometer is an improved version of the CS615 Water Content Reflectometer. The CS625 is a modified CS616 for use with the Campbell Scientific CR200 series dataloggers. The difference between the CS616 and the CS625 is the output voltage level. See the Sensor Specifications section for details.

Both Water Content Reflectometers are designed to measure volumetric water content of soils or other porous media. The water content information is derived from the probe sensitivity to the dielectric constant of the medium surrounding the probe rods.

The CS616 output is a square wave output and can be connected to Campbell Scientific dataloggers CR510, CR10X, CR23X, and CR5000. A special CS616 datalogger instruction (P138) is used to measure the probe output period which is converted to volumetric water content using calibration equations. Datalogger instructions for period averaging can also be used.

The CS625 output is a square wave output and can be connected to Campbell Scientific CR200 series dataloggers. A CRBasic program using Period Averaging is used to measure the probe output period and convert to volumetric water content using calibration equations.

The Water Content Reflectometer consists of two stainless steel rods connected to a printed circuit board. A shielded four-conductor cable is connected to the circuit board to supply power, enable the probe, and monitor the pulse output. The circuit board is encapsulated in epoxy.

High-speed electronic components on the circuit board are configured as a bistable multivibrator. The output of the multivibrator is connected to the probe rods which act as a wave guide. The travel time of the signal on the probe rods depends on the dielectric permittivity of the material surrounding the rods and the dielectric permittivity depends on the water content. Therefore, the oscillation frequency of the multivibrator is dependent on the water content of the media being measured. Digital circuitry scales the multivibrator output to an appropriate frequency for measurement with a datalogger. The Water Content Reflectometer output is essentially a square wave. The probe output period ranges from about 14 microseconds with rods in air to about 42 microseconds with the rods completely immersed in typical tap water. A calibration equation converts period to volumetric water content.

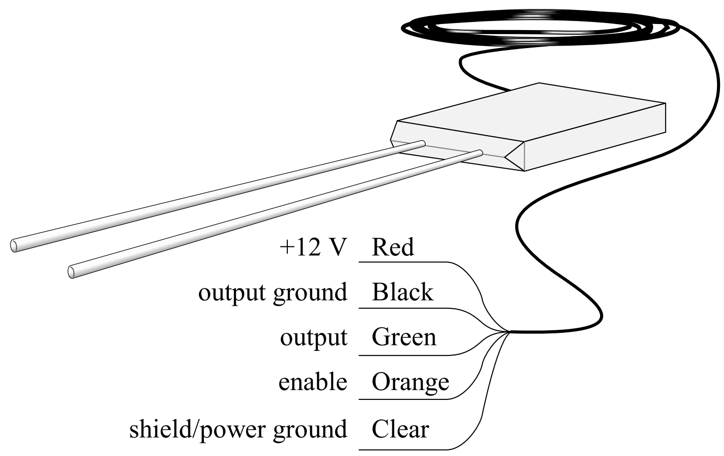

FIGURE 1. Water Content Reflectometer

2. Sensors Specifications

2.1 Dimensions

Rods: 300 mm long, 3.2 mm diameter, 32 mm spacing

Probe Head: 85 mm x 63 mm x 18 mm

2.2 Weight

Probe (without cable): 280 g

Cable: 35 g m^{-1}

2.3 Electrical Specifications

Output

CS616: ± 0.7 volt square wave with frequency dependent on water content

CS625: Zero to 3.3 volt square wave with frequency dependent on water content

Power

65 milliamps @ 12 VDC when enabled, 45 microamps quiescent

Power Supply Requirements

5 VDC minimum, 18 VDC maximum

Enable Voltage

4 VDC minimum, 18 VDC maximum

Maximum cable length

1000 feet (305 m)

Electromagnetic Compatibility

The CS616/CS625 is Œ compliant with performance criteria available upon request. RF emissions are below EN55022 limits if the CS616/CS625 is enabled less than 0.6 milliseconds and measurements are made at a 1 Hz (1 per second) or slower frequency. The CS616 instruction (P138) for the CR510, CR10X, and CR23X limits the enable time to less than 0.6 milliseconds. The CS616/CS625 meets EN61326 requirements for protection against electrostatic discharge and surge. As an unavoidable consequence of the principle of operation, external RF sources can affect CS616/CS625 measurements. Consequently, the CS616/CS625 circuitry should be located away from radio transmitter aerials and cables, or measurements ignored during RF transmissions.

Inter-probe Interference

The Water Content Reflectometer probe rods are antennae which both transmit and receive electromagnetic signals. Probes enabled simultaneously and within approximately 9 inches of each other can cause erratic measurements. If probes must be close to each other, configure the enable lines to the datalogger control ports so the probes are not enabled simultaneously.

2.4 Operational

The **accuracy** specification for the volumetric water content measurement using the CS616/CS625 probes is based on laboratory measurements in a variety of soils and over the water content range air dry to saturated. The soils were typically sandy loam and coarser. Silt and clay were present in some of the soils used to characterize accuracy.

The Water Content Reflectometer accuracy is ± 2.5% VWC using standard calibration with bulk electrical conductivity ≤ 0.5 deciSiemen meter^{-1} (dS m^{-1}) and bulk density ≤ 1.55 g cm^{-3} in measurement range 0% VWC to 50% VWC

Resolution is the minimum change in the dielectric permittivity that can reliably be detected by the Water Content Reflectometer. The CS616 or CS625 is typically used to measure soil volumetric water content. The resolution of the CS616/CS625 is better than 0.1 % volumetric water content.

Precision describes the repeatability of a measurement. It is determined for the CS616and CS625 by taking repeated measurements in the same material. The precision of the CS616/CS625 is better than 0.1 % volumetric water content.

Probe-to-probe variability: ± 0.5% VWC in dry soil, ± 1.5% VWC in typical saturated soil

Soil Properties

The Water Content Reflectometer operation can be affected when the signal applied to the probe rods is attenuated. The probe will provide a well-behaved response to changing water content, even in attenuating soils or other media, but the response may be different than described by the standard calibration. Consequently, a unique calibration is required. Change in probe response can occur when soil bulk electrical conductivity is greater than 0.5 dS m^{-1}. The major contributor to soil electrical conductivity is the presence of free ions in solution from dissolution of soil salts. Soil organic matter and some clays can also attenuate the signal.

3. Installation

3.1 Orientation

The probe rods can be inserted vertically into the soil surface or buried at any orientation to the surface. A probe inserted vertically into a soil surface will give an indication of the water content in the upper 30 cm of soil. The probe can be installed horizontal to the surface to detect the passing of wetting fronts or other vertical water fluxes. A probe installed at an angle of 30 degrees with the surface will give an indication of the water content of the upper 15 cm of soil.

3.2 Potential Problems with Improper 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 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 which generates air voids around the rods will reduce the 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.

4. Wiring

TABLE 1. CS616/625 wiring code.		
color	**function**	**datalogger connection**
red	+12 V	+12 V
green	output	SE analog channel
orange	enable	control port
black	signal ground	G
clear	shield (power ground)	G

NOTE Both the black ground wire and the clear shield wire must be connected to datalogger ground.

5. Datalogger Instructions and Programming

5.1 CS616/625 Outputs and Datalogger Instructions

The output of the CS616 is a square wave with amplitude ± 0.7 volts and a frequency that is dependent on the dielectric constant of the material surrounding the probe rods. Datalogger instruction 138 is specifically designed for the CR510, CR10X, and CR23X to measure the output period of the CS616. The period value is used in the calibration for water content. The period in air is approximately 14.7 microseconds, and the period in saturated soil with porosity 0.4 is approximately 31 microseconds. Datalogger instruction 27, Period Average, can also be used to measure CS616 output period.

The output of the CS625 is a square wave with amplitude zero to 3.3 volts and a frequency that is dependent on the dielectric constant of the material surrounding the probe rods. The CRBasic instruction PeriodAvg is used by the CR200 series dataloggers to measure the CS625 output period. The period value is used in the calibration for water content. The period in air is approximately 14.7 microseconds, and the period in saturated soil with porosity 0.4 is approximately 31 microseconds.

5.2 Measuring CS616 Output Using Datalogger Instruction 138

See section 5.4.1 for example on using Instruction 138.

```
1:  CS616 Water Content Reflectometer (P138)
  1:  1        Reps
  2:  00       SE Channel
  3:  00       Control Port Code
  4:  0000     Loc [ _________ ]
  5:  1.0      Mult
  6:  0.0      Offset
```

Reps: Enter the number of CS616s that will be measured with the instruction. The sensors must be wired in consecutive channels. Each measurement uses the same multiplier and offset. The option chosen in parameter 3 will determine whether subsequent repetitions are enabled with the next higher control port or with the same control port.

SE CHAN: Enter the single-ended analog channel where the sensor's green wire is connected. When Reps is greater than 1, this entry is the channel for the first CS616.

PORT: Enter an integer to specify the control port that will be used to enable the CS616 sensor. For the CR510, only C1 can be used to enable a CS616.

Code	Control Port Option
X	X specifies the first control port that will be used. Subsequent repetitions will be enabled with the next sequential control port. Control port 1 follows control port 8 in a sequence.
1X	All repetitions will be enabled with a single specified control port. Simultaneously enabling several CS616s can result in exceeding power supply capacity.

LOC: Enter the input location that will store the period measurement. The period output is in microseconds.

An Input Location is a place in the datalogger's memory where a measurement is temporarily stored until it is used in intermediate storage, output, or overwritten. An input location is reserved for each measurement in the datalogger program. Additional locations can be created by the user.

MULT: A factor that the input location value is multiplied by. Enter a 1 for probe output period in microseconds.

A multiplier is often used for calibration or to convert the input location value to different units.

OFFSET: A constant that is added to the input location value. An offset of 0 has no effect on the input location value.

An offset is often used for calibration or to convert the data to different units.

With a multiplier of 1 and an offset of 0, P138 returns the period in microseconds.

5.3 Measuring CS616 Output Using CR10X, CR23X Period Averaging Instruction 27

See section 5.4.2 for example on using Instruction 27.

```
1:  Period Average (SE) (P27)
  1:  1        Reps
  2:  00       Range Option
  3:  00       SE Channel
  4:  0000     No. of Cycles
  5:  0000     Timeout (units = 0.01 seconds)
  6:  0000     Loc [ _________ ]
  7:  1.0      Mult
  8:  0.0      Offset
```

Reps: Enter the number of CS616s that will be measured with the instruction. The sensors must be wired in consecutive channels. Each measurement uses the same multiplier and offset.

Range Option: Enter 2-digit integer to choose output as period in microseconds and range. Suggested value for CS616 is 04.

Code	Max. Freq.
x1	8 kHz @ 2 mV peak-to-peak
x2	20 kHz @ 3 mV peak-to-peak
x3	50 kHz @ 12 mV peak-to-peak
x4	200 kHz @ 2 V peak-to-peak

Where: x = 0 Output period in microseconds
x = 1 Output frequency in kHz

SE CHAN: Enter the single-ended analog channel where the sensor green wire is connected. When Reps are greater than 1, this entry is the channel for the first CS616.

No. of Cycles: Enter the number of cycles of the input signal the instruction uses to determine period. A value of 100 is recommended.

Timeout: Enter the maximum amount of time for the no. of cycles to occur. A value of 1 (10 millisecond) is recommended.

LOC: Enter the input location that will store the period measurement. The period output is in microseconds.

An Input Location is a place in the datalogger's memory where a measurement is temporarily stored until it is used in intermediate storage, output, or overwritten. An input location is reserved for each measurement in the datalogger program. Additional locations can be created by the user.

MULT: A factor that the input location value is multiplied by.

A multiplier is often used for calibration or to convert the input location value to different units.

OFFSET: A constant that is added to the input location value. An offset of 0 has no effect on the input location value.

An offset is often used for calibration or to convert the data to different units.

With a multiplier of 1 and an offset of 0, P27 returns the period in microseconds or frequency in kHz as selected by parameter 2.

5.4 Sample Programs for CS616

TABLE 2. CS616 Sample Programs

Sample Program Number	Program Description
1	Set Flag 1 to read output of one CS616 using CR10X instruction 138 and convert output period to volumetric water content
2	Every 5 minutes, measure CS616 output period using instruction 27 and convert to volumetric water content. Write hourly average to datalogger final storage.
3	Read datalogger battery voltage and 3 CS616s hourly. Convert CS616 period to volumetric water content. Write average of hourly readings to final storage every 4 hours.
4	Measure soil temperature and CS616 output period every 4 hours. Correct CS616 output period for temperature and write result to datalogger final storage.
5	Hourly, measure datalogger battery voltage, internal temperature and 48 CS616 probes using AM16/32 multiplexer.

5.4.1 CS616 Sample Program 1

Set Flag 1 to read output of one CS616 using CR10X instruction 138 and convert output period to volumetric water content

CS616	CR10X
green	Single-Ended Channel 1 (SE1)
orange	Control Port 1 (C1)

The red lead is connected to 12 VDC and the black and shield are connected to ground.

```
;{CR10X}
;
;Set Flag 1 high for single water content reading.
;Result stored in input storage only
;
*Table 1 Program
  01: 1              Execution Interval (seconds)

1:  If Flag/Port (P91)
  1:   11            Do if Flag 1 is High
  2:   30            Then Do

2:  CS616 Water Content Reflectometer (P138)
  1:   1             Reps
  2:   1             SE Channel
  3:   1             C1 is first of sequential Control Ports used
  4:   1             Loc [ period    ]
  5:   1.0           Mult
  6:   0.0           Offset

3:  Polynomial (P55)
  1:   1             Reps
  2:   1             X Loc [ period    ]
  3:   2             F(X) Loc [ VWC       ]
  4:   -0.0663       C0
  5:   -0.0063       C1
  6:   0.0007        C2
  7:   0.0           C3
  8:   0.0           C4
  9:   0.0           C5

4:  Do (P86)
  1:   21            Set Flag 1 Low

5:  End (P95)

*Table 2 Program
  02: 0.0000         Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 period    1 0 1
2 VWC       1 0 1
```

5.4.2 CS616 Sample Program 2

Every 5 minutes, measure CS616 output period using instruction 27 and convert to volumetric water content. Write hourly average to datalogger final storage.

CS616	CR10X
green	Single-Ended Channel 1 (SE1)
orange	Control Port 1 (C1)

The red lead is connected to 12 VDC and the black and shield are connected to ground.

```
;{CR10X}
;
*Table 1 Program
  01: 300         Execution Interval (seconds)

1:  Do (P86)                                    ;Enable/Turn On the CS616 probe.
  1:   41         Set Port 1 High

2:  Period Average (SE) (P27)
  1:   1          Reps
  2:   4          200 kHz Max Freq @ 2 V Peak to Peak, Period Output
  3:   1          SE Channel
  4:   100        No. of Cycles
  5:   1          Timeout (0.01 sec units)
  6:   1          Loc [ period    ]
  7:   1.0        Mult
  8:   0.0        Offset

3:  Polynomial (P55)
  1:   1          Reps
  2:   1          X Loc [ period    ]
  3:   2          F(X) Loc [ vwc      ]
  4:   -0.0663    C0
  5:   -0.0063    C1
  6:   0.0007     C2
  7:   0.0        C3
  8:   0.0        C4
  9:   0.0        C5

4:  Do (P86)                                    ;Turn Off CS616 probe
  1:   51         Set Port 1 Low

5:  If time is (P92)                            ;Turn On Data Storage every hour
  1:   0          Minutes (Seconds --) into a
  2:   60         Interval (same units as above)
  3:   10         Set Output Flag High (Flag 0)

6:  Real Time (P77)                             ;Store a time stamp.
  1:   1220       Year,Day,Hour/Minute (midnight = 2400)

7:  Average (P71)                               ;Store the average VWC.
  1:   1          Reps
  2:   2          Loc [ vwc      ]
```

```
*Table 2 Program
  02: 0.0000        Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 period    1 1 1
2 vwc       1 1 1
```

5.4.3 CS616 Sample Program 3

Read datalogger battery voltage and 3 CS616s hourly. CS616 enable wires are connected to sequential datalogger control ports for automatic incrementing. Convert CS616 period to volumetric water content. Write average of hourly readings to final storage every 4 hours.

CS616x	**CR10X**
green	Single-Ended Channel x (SEx)
orange	Control Port y (Cy)

x = 1,2,3 for 3 CS616 outputs

y = 6,7,8 for 3 CS616s enables

The red leads are connected to 12VDC and the blacks and shields are connected to ground.

```
;{CR10X}
;
*Table 1 Program
  01: 3600          Execution Interval (seconds)

1:  Batt Voltage (P10)
  1:   7            Loc [ batt      ]

2:  CS616 Water Content Reflectometer (P138)
  1:   3            Reps
  2:   1            SE Channel
  3:   6            C6 is first of sequential Control Ports used
  4:   1            Loc [ period_1  ]
  5:   1.0          Mult
  6:   0.0          Offset
```

```
3:  Polynomial (P55)
   1:   3               Reps
   2:   1               X Loc [ period_1  ]
   3:   4               F(X) Loc [ vwc_1     ]
   4:   -0.0663         C0
   5:   -0.0063         C1
   6:   0.0007          C2
   7:   0.0             C3
   8:   0.0             C4
   9:   0.0             C5

;
4:  If time is (P92)
   1:   0000            Minutes (Seconds --) into a
   2:   240             Interval (same units as above)
   3:   10              Set Output Flag High (Flag 0)

5:  Average (P71)
   1:   4               Reps
   2:   4               Loc [ vwc_1     ]

*Table 2 Program
   02:  0.0000          Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 period_1  5 1 1
2 period_2  9 1 1
3 period_3  17 1 1
4 vwc_1     5 1 1
5 vwc_2     9 1 1
6 vwc_3     17 1 1
7 batt      1 0 1
```

5.4.4 CS616 Sample Program 4

Measure soil temperature with 107 probe and CS616 output period every four hours. Correct CS616 output period for temperature and write result to datalogger final storage.

Sensor lead	**CR10X**
CS616 green	Single-Ended Channel 2 (SE2)
CS616 orange	Control Port 4 (C4)
107 red	Single-Ended Channel 1 (SE1)
107 black	Excitation 1 (E1)
107 purple	Analog Ground (AG)
107 clear	Ground (G)

The CS616 red leads are connected to 12 VDC and the blacks and shields are connected to ground.

```
;{CR10X}
;
*Table 1 Program
  01: 60            Execution Interval (seconds)

;set reference temperature for temperature correction
1:  Z=F x 10^n (P30)
  1:  20            F
  2:  0              n, Exponent of 10
  3:  2             Z Loc [ Tref     ]

2:  If time is (P92)
  1:  0000          Minutes (Seconds --) into a
  2:  240           Interval (same units as above)
  3:  30            Then Do

3:  Temp (107) (P11)                              ;Measure soil temperature.
  1:  1             Reps
  2:  1             SE Channel
  3:  1             Excite all reps w/E1
  4:  1             Loc [ TSoil    ]
  5:  1.0           Mult
  6:  0.0           Offset

4:  CS616 Water Content Reflectometer (P138)
  1:  1             Reps
  2:  2             SE Channel
  3:  4             C4 is first of sequential Control Ports used
  4:  3             Loc [ CS616    ]
  5:  1.0           Mult
  6:  0.0           Offset

;The following four instructions correct CS616 period for soil temperature
;using the equation given in section 5.8 of the CS616 manual.
;The corrected period is stored as variable NewCS616.

5:  Polynomial (P55)
  1:  1             Reps
  2:  3             X Loc [ CS616    ]
  3:  4             F(X) Loc [ TempCS616 ]
  4:  0.526         C0
  5:   -0.052       C1
  6:  0.00136       C2
  7:  0.0           C3
  8:  0.0           C4
  9:  0.0           C5

6:  Z=X-Y (P35)
  1:  2             X Loc [ Tref     ]
  2:  1             Y Loc [ TSoil    ]
  3:  5             Z Loc [ TFactor  ]
```

```
7:  Z=X*Y (P36)
   1:   5              X Loc [ TFactor   ]
   2:   4              Y Loc [ TempCS616 ]
   3:   4              Z Loc [ TempCS616 ]

8:  Z=X+Y (P33)
   1:   3              X Loc [ CS616     ]
   2:   4              Y Loc [ TempCS616 ]
   3:   6              Z Loc [ NewCS616  ]

9:  Polynomial (P55)                      ;Convert corrected probe period to water content.
   1:   1              Reps
   2:   6              X Loc [ NewCS616  ]
   3:   7              F(X) Loc [ WaterCont ]
   4:   -0.0663        C0
   5:   -0.0063        C1
   6:   0.0007         C2
   7:   0.0            C3
   8:   0.0            C4
   9:   0.0            C5

10:  Do (P86)
   1:   10             Set Output Flag High (Flag 0)

11:  Real Time (P77)                      ;Record time of measurement.
   1:   0220           Day,Hour/Minute (midnight = 2400)

12:  Sample (P70)                         ;Write water content to datalogger final storage.
   1:   1              Reps
   2:   7              Loc [ WaterCont ]

13:  End (P95)

*Table 2 Program
   02:  0.0000         Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 TSoil     1 1 1
2 Tref      1 1 1
3 CS616     1 2 1
4 TempCS616 1 2 2
5 TFactor   1 1 1
6 NewCS616  1 1 1
7 WaterCont 1 1 1
```

5.4.5 CS616 Sample Program 5

Hourly, measure datalogger battery voltage, internal temperature and 48 CS616 probes. The AM16/32 slide switch on the top panel is set to 4X16. Can execute measurement sequence manually by setting Flag 1 high.

Sensor lead	**AM16/32**	**CR10X**
CS616-1 green	1H	
CS616-2 green	1L	
CS616-3 green	2H	
CS616-1,2,3 orange	2L	
CS616-4 green	3H	
CS616-5 green	3L	
CS616-6 green	4H	
CS616-4,5,6 orange	4L	
...	…	
CS616-46 green	31H	
CS616-47 green	31L	
CS616-48 green	32H	
CS616-46,47,48	32L	
	RES	C1
	CLK	C2
	COM ODD H	SE1
	COM ODD L	SE2
	COM EVEN H	SE3
	COM EVEN L	C3

```
;{CR10X}
;
*Table 1 Program
  01: 60          Execution Interval (seconds)

1:  Batt Voltage (P10)          ;Measure battery voltage
  1:   1          Loc [ Bat_Volt  ]

2:  Internal Temperature (P17)  ;Measure datalogger internal temperature
  1:   2          Loc [ DL_Temp   ]

3:  If time is (P92)            ;Every 60 Minutes Start Multiplexer Measurement Loop
  1:   0          Minutes (Seconds --) into a
  2:   60         Interval (same units as above)
  3:   11         Set Flag 1 High

4:  If Flag/Port (P91)          ;User can start Measurement Loop by setting Flag 1 High
  1:   11         Do if Flag 1 is High
  2:   30         Then Do
```

```
5:  Do (P86)                          ;Set control port 1 high (i.e. Reset Multiplexer)
  1:   41            Set Port 1 High

6:  Beginning of Loop (P87)           ;16 loops X 3ea CS616 measured/loop
  1:   0             Delay
  2:   16            Loop Count

7:  Step Loop Index (P90)             ;Increment input locations by 3/loop pass
  1:   3             Step

8:  Do (P86)
  1:   72            Pulse Port 2     ;Pulse control port 2 (i.e. Multiplier Clock)

9:  CS616 Water Content Reflectometer (P138) ;Measure Period on 3ea CS616
  1:   3             Reps
  2:   1             SE Channel
  3:   13            All reps use C3
  4:   3             -- Loc [ Period_1  ]
  5:   1.0           Mult
  6:   0.0           Offset
;Note: Input "Loc" must be indexed "--" in a loop! How? Use the "F4" Key.

10:  End (P95) ;end of loop

11:  Do (P86)                          ;Set user flag 1 low
  1:   21            Set Flag 1 Low

12:  End (P95)                         ;Do Loop End instruction

13:  Do (P86)                          ;Set control port 1 "low" (i.e. Multiplexer Reset)
  1:   51            Set Port 1 Low

14:  Polynomial (P55)                  ;Convert 48ea Period measurements into water content
  1:   48            Reps
  2:   3             X Loc [ Period_1  ]
  3:   52             F(X) Loc [ VWC_1     ]
  4:   -0.0663       C0
  5:   -0.0063       C1
  6:   0.0007        C2
  7:   0.0           C3
  8:   0.0           C4
  9:   0.0           C5

15:  If time is (P92)                  ;Store hourly averages every 4 hours
  1:   0             Minutes (Seconds --) into a
  2:   240           Interval (same units as above)
  3:   10            Set Output Flag High (Flag 0)

16:  Real Time (P77)                   ;Data Storage time stamp
  1:   1220          Year,Day,Hour/Minute (midnight = 2400)

17:  Average (P71)                     ;Data Storage Average, Location 1 & 2
  1:   2             Reps
  2:   1             Loc [ Bat_Volt  ]
```

```
18:  Average (P71)                    ;Data Storage Average, Location 52,53,..99
   1:   48              Reps
   2:   52              Loc [ VWC_1     ]

*Table 2 Program
   02:  0.0000         Execution Interval (seconds)

*Table 3 Subroutines

End Program

-Input Locations-
1 Bat_Volt  1 1 1
2 DL_Temp   1 1 1
3 Period_1  7 1 1
4 Period_2  11 1 1
.
.
50 Period_48 19 1 0
51 _________ 0 0 0
52 VWC_1     5 1 1
53 VWC_2     9 1 1
.
.
99 VWC_48    17 1 1
```

5.5 Measuring CS625 Output Using CR200 PeriodAvg Instruction

The PeriodAvg instruction is used to measure the period (in microseconds) or the frequency (in kHz) of a signal on a single-ended channel. This instruction can be used to measure the CS625 water content reflectometer.

PeriodAvg(Dest, SEChan, Option, Cycles, Timeout, Port, Mult, Offset)

Dest The Dest parameter is a variable in which to store the results of the measurement.

SEChan The SEChan argument is the number of the single-ended channel on which to make the measurement. Valid options are analog channels 1 through 4. The green wire is connected to this channel number.

Option The Option parameter specifies whether to output the frequency or the period of the signal.

Code	Description
0	Period of the signal is returned (msec)
1	Frequency of the signal is returned (Hz)

Code 0 is typically used with the CS625 with a multiplier (see below) of 1000 to convert to microseconds.

Cycles The Cycles parameter specifies the number of cycles to average each scan. The specified number of cycles are timed with a resolution of 70 ns, making the resolution of the period measurement 70 ns divided by the number of Cycles measured. A value of 10 is recommended for the CS625.

Timeout The Timeout parameter is the maximum time duration, in milliseconds, that the datalogger will wait for the number of Cycles to be measured for the average calculation. An overrange value will be stored if the Timeout period is exceeded. A value of 1 is recommended if 10 is used for cycles parameter.

Port The Port parameter is the control port or analog channel that will be used to switch power to the CS625 water content reflectometer. Valid options are:

Code	Description
0	None
C1	Control Port 1
C2	Control Port 2
3	Analog Channel 3
4	Analog Channel 4
5	Analog Channel 5
P_SW	Analog Channel 6/P_SW

Mult, Offset The Mult and Offset parameters are each a constant, variable, array, or expression by which to scale the results of the raw measurement. A multiplier value of 1000 is recommended to convert CS625 period to microseconds.

5.6 Sample Programs for CS625

TABLE 3. CS625 Sample Programs

Sample Program Number	Program Description
1	Measure temperature with 109 probe and volumetric water content with 4 CS625 hourly. Store average hourly readings to final storage every 4 hours.
2	Measure temperature with 109 probe and use the 109 temperature to correct the period for 1 CS625. Use standard calibration equation to convert temperature-corrected period to volumetric water content. Sensors are read hourly and average water content and temperature are written to storage every 4 hours.

5.6.1 CS625 Sample Program 1

Hourly measure temperature with 109 probe and volumetric water content with 4 CS625. Store average hourly readings to final storage every 4 hours.

CS625 leads	**CR200**
greens	Single-Ended Channel 1 thru 4 (SE1-4)
blacks	associated grounds for SE1-4
oranges	Control Port 1 (C1)
reds	SW Battery
clears	G
109 leads	**CR200**
black	switch excitation channel 1 EX1
red	Single-Ended Channel 5 (SE5)
purple	G
clear	G

```
'CR200 program to read 4 CS625s and 1 109 temperature probe.
'Standard calibration is used to convert CS625 output
'period to volumetric water content.
'Sensors are read hourly and average water content and
'temperature are written to storage every 4 hours.

'Declare Variables
Public temperature
Dim period(4),vwc(4)
Dim i

'Declare Constants
Const a0=-0.0663
Const a1=-0.0063
Const a2=0.0007

'Define Data Tables
DataTable (ofile,1,10)
 DataInterval (0,4,hr)
 Average(1,temperature,0)
 Average (1,vwc,0)
EndTable
```

```
'Main Program
BeginProg
  Scan (1,hr)
  Therm109 (temperature,1,5,Ex1,1.0,0)
  SWBatt (1 )
  For i=1 To 4
   PeriodAvg (period(i),1,0,10,10,C1,1,0)
   vwc(i) = a0 + a1*period(i) + a2*period(i)^2
  Next i
  CallTable ofile
  NextScan
EndProg
```

5.6.2 CS625 Sample Program 2

Measure temperature with 109 probe and use the 109 temperature to correct the period for 1 CS625. Use standard calibration equation to convert temperature-corrected period to volumetric water content. Sensors are read hourly and average water content and temperature are written to storage every 4 hours.

CS625 leads	**CR200**
green	Single-Ended Channel 1 (SE1)
black	ground for SE1
orange	Control Port 1 (C1)
red	SW Battery
clear	G
109 leads	**CR200**
black	Switched excitation channel 1 (EX1)
red	Single-Ended Channel 5 (SE5)
purple	G
clear	G

```
'CR200 program to read 1 109 temperature probe and 1 CS625.
'Use temperature to correct CS625 period.
'Standard calibration is used to convert CS625 output
'period to volumetric water content.
'Sensors are read hourly and average water content and
'temperature are written to storage every 4 hours.

'Declare Variables
Public Tsoil
Public uncorrected,corrected
Public vwc
```

```
'Declare Constants
'Water content calibration constants
Const a0=-0.0663
Const a1=-0.0063
Const a2=0.0007
'Temperature correction constants
Const t0=0.526
Const t1=-0.052
Const t2=0.00136
'Reference temperature
Const Tref=20

'Define Data Tables
DataTable (ofile,1,10)
 DataInterval (0,4,hr)
 Average(1,Tsoil,0)
 Average (1,vwc,0)
EndTable

'Main Program
BeginProg
  Scan (1,hr)
  Therm109 (Tsoil,1,5,Ex1,1.0,0)
  SWBatt (1)
  PeriodAvg (uncorrected,1,0,10,10,C1,1,0)
  SWBatt (0)
  corrected=uncorrected+(Tref-Tsoil)*(t0+t1*uncorrected+t2*uncorrected^2)
  vwc = a0 + a1*corrected + a2*corrected^2
  CallTable ofile
  NextScan
EndProg
```

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

6.1 Description of Measurement Method

The Water Content Reflectometer method for measuring soil water content is an indirect measurement that is sensitive to the dielectric permittivity of the material surrounding the probe rods. Since water is the only soil constituent that (1) has a high value for dielectric permittivity and (2) is the only component other than air that changes in concentration, a device sensitive to dielectric permittivity can be used to estimate volumetric water content

The fundamental principle for CS616/CS625 operation is that an electromagnetic pulse will propagate along the probe rods at a velocity that is dependent on the dielectric permittivity of the material surrounding the line. As water content increases, the propagation velocity decreases because polarization of water molecules takes time. The travel time of the applied signal along 2 times the rod length is essentially measured.

The applied signal travels the length of the probe rods and is reflected from the rod ends traveling back to the probe head. A part of the circuit detects the reflection and triggers the next pulse.

The frequency of pulsing with the probe rods in free air is about 70 MHz. This frequency is scaled down in the Water Content Reflectometer circuit output stages to a frequency easily measured by a datalogger. The probe output frequency or period is empirically related to water content using a calibration equation.

6.2 Response Curves

Figure 2 shows calibration data collected during laboratory measurements in a loam soil with bulk density 1.4 g cm^{-3} and bulk electrical conductivity at saturation of 0.4 dS m^{-1}. For this soil, the saturation bulk electrical conductivity of 0.4 dS m^{-1} corresponds to laboratory electrical conductivity using extraction methods of about 2 dS m^{-1}.

The response is accurately described over the entire water content range by a quadratic equation. However, in the typical water content range of about 10% to about 35% volumetric water content, the response can be described with slightly less accuracy by a linear calibration equation. The manufacturer supplied quadratic provides accuracy of ± 2.5% volumetric water content for soil electrical conductivity ≤ 0.5 dS m^{-1} and bulk density ≤ 1.55 g cm^{-3} in a measurement range of 0% VWC to 50% VWC.

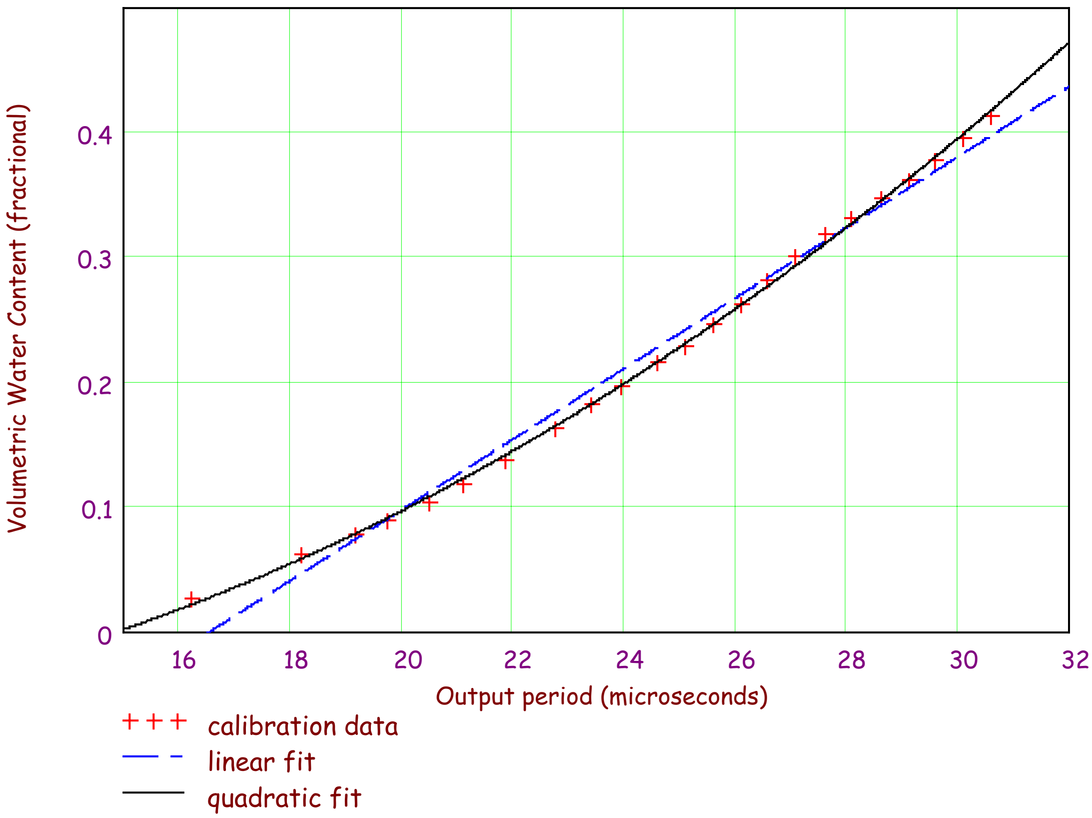

FIGURE 2. CS616 and CS625 Linear and Quadratic Calibrations Derived from Loam Soil.

Figure 3 compares the CS616/CS625 response in the Figure 2 loam soil to a higher density sandy clay loam for two different electrical conductivities. The bulk density for both sandy clay loam soils is 1.6 g cm^{-3}. The electrical conductivity at saturation for the sandy clay loam labeled *compacted soil* is 0.4 dS m^{-1}. The *compacted soil, high EC* had an electrical conductivity at saturation of 0.75 dS m^{-1}.

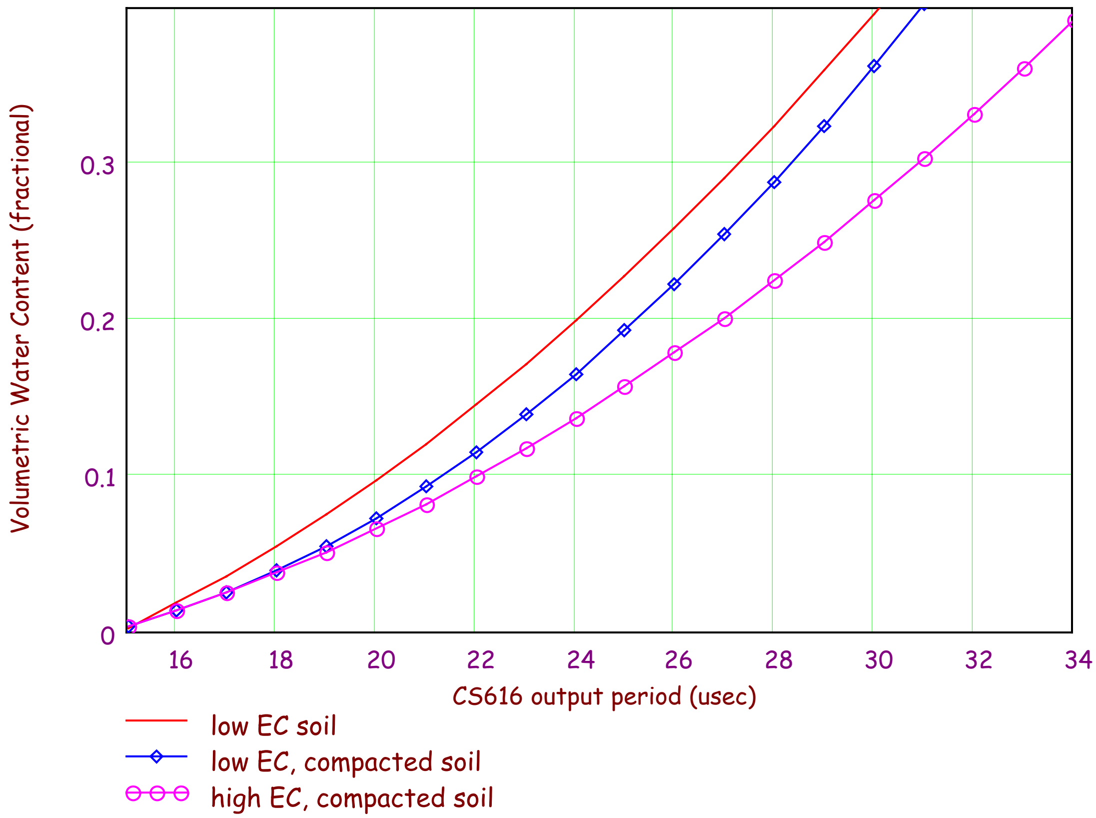

FIGURE 3. CS616 and CS625 response for low EC loam with bulk density 1.4 g cm^{-3}, a low EC sandy clay loam with bulk density 1.6 g cm^{-3}, and a high EC sandy clay loam with bulk density 1.6 g cm^{-3}.

The *compacted soil* response shows the effect of compaction and high clay content. The signal attenuation caused by compaction or high clay content causes an offset in the response as shown by the near-parallel curves at water contents above 10%. This is the effect of attenuation by the solid phase.

The effect of increased electrical conductivity for the same soil is shown by the response curve *high EC, compacted soil,*. Higher electrical conductivity causes a decrease in the slope of the response curve. This is the effect of attenuation by the solution phase.

6.3 Calibration Equations

Table 1 lists the calibration coefficients derived in the Campbell Scientific soils laboratory. Both linear and quadratic forms are presented. The choice of linear or quadratic forms depends on the expected range of water content and accuracy requirements. These coefficients should provide accurate volumetric water content in mineral soils with bulk electrical conductivity less than 0.5 dS m^{-1}, bulk density less than 1.55 g cm^{-3} , and clay content less than 30%.

TABLE 4. Standard calibration coefficients for linear and quadratic forms.				
Linear		quadratic		
C0	C1	C0	C1	C2
-0.4677	0.0283	-0.0663	-0.0063	0.0007

The linear equation is

$$VWC = -0.4677+0.0283*period .$$

The quadratic equation is

$$VWC = -0.0663 - 0.0063*period + 0.0007*period^2 .$$

Period is in microseconds. The result of both calibration equations is volumetric water content on a fractional basis. Multiply by 100 to express in percent volumetric water content.

Figure 4 shows the difference between the linear and quadratic calibration forms over the typical range. A CS616/CS625 output period of 16 microseconds is about 2% VWC and 32 microseconds is 47.25%. The linear calibration is within ± 1.25% VWC of the quadratic with underestimation of water content at wet and dry ends of the range and overestimates by up to about 1.2 % VWC at about 20% VWC.

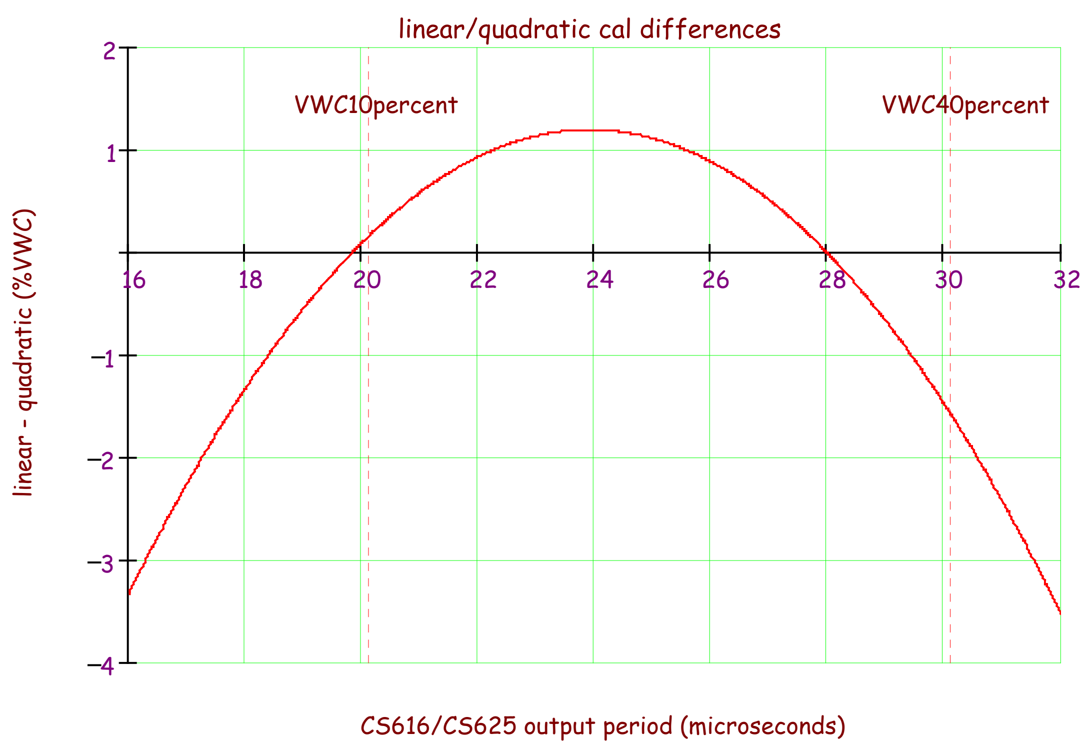

FIGURE 4. Difference in % volumetric water content between linear and quadratic forms of calibrations.

The linear and quadratic coefficients for the sandy clay loam data in FIGURE 3 follow and can be used in similar soils.

TABLE 5. Calibration coefficients for sandy clay loam with bulk density 1.6 g cm^{-3} and electrical conductivity at saturation 0.4 dS m^{-1} for both linear and quadratic forms.

Linear		quadratic		
C0	C1	C0	C1	C2
-0.6200	0.0329	0.0950	-0.0211	0.0010

TABLE 6. Calibration coefficients for sandy clay loam with bulk density 1.6 g cm^{-3} and electrical conductivity at saturation 0.75 dS m^{-1} for both linear and quadratic forms.

Linear		quadratic		
C0	C1	C0	C1	C2
-0.4470	0.0254	-0.0180	-0.0070	0.0006

6.4 Operating Range

6.4.1 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 CS616/CS625 is predominantly affected by changing dielectric constant 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; 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 CS616/CS625 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 same water content. Discussion of the effects of soil electrical conductivity on CS616/CS625 performance will be on a soil solution or extract basis unless stated otherwise.

When soil solution electrical conductivity values exceed 2 dS m^{-1}, the response of the CS616/CS625 output begins to change. The slope decreases with increasing electrical conductivity. The probe will still respond to water content changes with good stability, but the calibration will have to be modified. (See the Calibration section.) At electrical conductivity values greater than 5 dS m^{-1} the probe output can become unstable.

6.4.2 Soil Organic Matter, Clay Content and Soil Bulk Density

The amount of organic matter and clay in a soil can alter the response of dielectric-dependent methods to changes in water content. This is apparent when mechanistic models are used to describe this measurement methodology.

The electromagnetic energy introduced by the probe acts to re-orientate or polarize the water molecules. If other forces are acting on the polar water molecules, the force exerted by the applied signal will be less likely to polarize the molecules. This has the net effect of 'hiding' some of the water from the probe. Additionally, some clays sorb water interstitially and thus inhibit polarization by the applied field.

Organic matter and some clays are highly polar. These solid constituents can affect CS616/CS625 response to water content change and require specific calibration. This affect is opposite to that of the 'hiding' effect. It would be convenient if the calibration of water content to CS616/CS625 output period could be adjusted according to some parameter of the soil which reflects the character of the signal attenuation. However, such a parameter has not been identified.

The response of the Water Content Reflectometer to changing water content has been shown to change for some soils when bulk density exceeds 1.5 g cm^{-3}. The response to changing water content is still well behaved, but the slope will decrease with increasing bulk density.

6.5 Error Sources in Water Content Reflectometer Measurement

6.5.1 Probe-to-Probe Variability Error

All manufactured CS616s/CS625s are checked in standard media. The limits for probe response in the standard media ensure accuracy of ± 2% volumetric water content.

6.5.2 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.

6.5.3 Signal Attenuation Error

Section 6.1 presents a detailed description of CS616/CS625 operation. In summary, the CS616/CS625 is primarily sensitive to the dielectric permittivity of the material surrounding the probe rods. The propagation of electromagnetic energy along the probe rods depends on the dielectric properties of the medium. When the reflection of the applied signal from the end of the rods is detected by the CS616/CS625 circuit, another pulse is applied. The time between pulses depends on the propagation time, and the associated period is empirically related to volumetric water content.

The applied signal is subject to attenuation from losses in the medium being measured. While this does not directly affect propagation time, it causes delays in detection of the reflected signal. Attenuation of the signal will occur if there are free ions in soil solution, polar solid constituents such as organic matter or some clay, or conductive mineral constituents.

The general calibration equation for the CS616/CS625 will provide good results with attenuation equivalent to about 0.5 dS m^{-1} bulk electrical conductivity. Between 0.5 dS m^{-1} and 5 dS m^{-1}, the CS616/CS625 will continue to give a well-behaved response to changes in water content but a soil specific calibration is required. See section 10 for calibration information.

6.6 Temperature Dependence and Correction

The error in measured volumetric water content caused by the temperature dependence of the CS616/CS625 is shown in Figure 5. The magnitude of the temperature sensitivity changes with water content. Laboratory measurements were performed at various water contents and over the temperature range from 10°C to 40°C to derive a temperature correction for probe output period. The following equation can be used to correct the CS616/CS625 output period, $\tau_{uncorrected}$, to 20°C knowing the soil temperature, T_{soil}. See sample datalogger programs. The temperature correction assumes that both the water content and temperature do not vary over the length of the probes rods.

$$\tau_{corrected}(T_{soil}) = \tau_{uncorrected} + (20 - T_{soil}) * (0.526 - 0.052 * \tau_{uncorrected} + 0.00136 * \tau_{uncorrected}^{2})$$

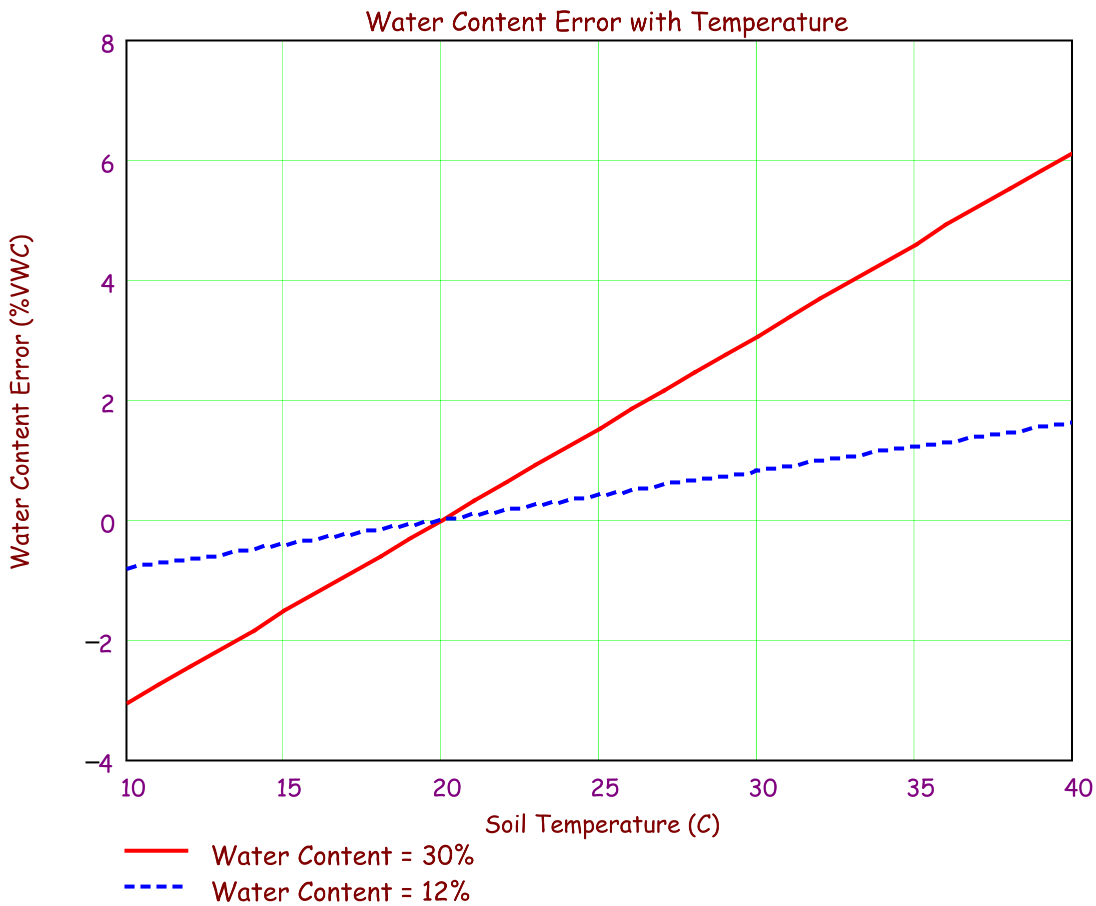

FIGURE 5. Percent volumetric water content error corrected for by temperature correction equation.

7. Water Content Reflectometer User-Calibration

7.1 Signal Attenuation in Conductive Soils and Need for Site-Specific Calibration

A shift in Water Content Reflectometer response results if the applied signal is attenuated significantly. There is a voltage potential between the probe rods when a pulse is applied to them. If the material between the rods is electrically conductive, a path for current flow exists and the applied signal is attenuated. Since the parallel rod design in soil is inherently a lossy medium and attenuation is frequency dependent, both the amplitude of the reflection and the rise-time or bandwidth are affected. Instead of a relatively short rise-time return pulse, the rise-time is greater and the amplitude is less.

The reflected signal must exceed a set amplitude before the next pulse is triggered. Reflections that are attenuated and have longer rise-times will take longer to be detected and trigger the next pulse leading to decreased frequency or increased period in conductive materials.

Some clays are very polar and/or conductive and will also attenuate the applied signal. Additionally, if the clayey soil is compacted, increased bulk density, the conductivity is increased and the response is affected.

Given the Water Content Reflectometer response to changing water content in attenuating media changes as described above, the accuracy of the volumetric water content measurement can be optimized by characterizing the probe response in the specific medium to be measured. The result is a specific calibration equation for a particular medium.

The precision and the resolution of the Water Content Reflectometer measurement are not affected by attenuating media. Both precision and resolution are better than 0.1% volumetric water content.

7.2 The User-Derived Calibration Equation

The probe output response to changing water content is well described by a quadratic equation, and, in many applications, a linear calibration gives required accuracy.

Quadratic form:

$$\theta_v(\tau) = C_0 + C_1 * \tau + C_2 * \tau^2$$

with θ_v , the volumetric water content ($m^3\ m^{-3}$); τ, the CS616/CS625 period (microseconds); and C_n , the calibration coefficient. The standard calibration coefficients are derived from factory laboratory measurements using curve fitting of known volumetric water content to probe output period.

Linear form:

$$\theta_v(\tau) = C_0 + C_1 * \tau$$

with θ_v , the volumetric water content ($m^3\ m^{-3}$); τ, the Water Content Reflectometer period (microseconds); C_o , the intercept; and C_1 , the slope.

Two data points from careful measurements can be enough to derive a linear calibration. A minimum of 3 data points is needed for a quadratic. With 3 evenly spaced water contents covering the expected range, the middle water content data point will indicate whether a linear or quadratic calibration equation is needed.

Note from figures 2 and 3 that the calibration function describing the CS616/CS625 response to changing water content is always concave up. If calibration data suggests a different shape, there may be a problem with the data or method.

7.3 Collecting Laboratory Data for Calibration

Water Content Reflectometer Data needed for CS616/CS625 calibration are the CS616/CS625 output period (microseconds) and an independently determined volumetric water content. From this data, the probe response to changing water content can be described by a quadratic calibration equation of the form

$$\theta_v(\tau) = C_0 + C_1 * \tau + C_2 * \tau^2$$

with θ_v being the volumetric water content (m^3 m^{-3}); τ, the CS616 period (microseconds); and C_n , the calibration coefficient (n = 0..2).

The linear form is

$$\theta_v(\tau) = C_0 + C_1 * \tau$$

with θ_v , the volumetric water content (m^3 m^{-3}); τ, the CS616 period (microseconds); C_o , the intercept; and C_1 , the slope.

Required equipment:

1. CS616/CS625 connected to datalogger programmed to measure output period

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 weight

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 output period. The number of data sets needed to derive a calibration depends on whether the linear or quadratic form is being used and the accuracy requirement. Consider the expected range of soil water content while viewing Figure 2 and Figure 3. If the expected response is nearly linear, fewer laboratory measurements are needed to derive the calibration. A linear response is best described by data taken near the driest and wettest 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 2.5 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 10 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 may be necessary.

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 the top of the existing compacted layer.

The container to hold the soil during calibration should be large enough that the rods of the probe are no closer than about 2 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 output period. Repeat previous step and this step 3 or 4 times.

Determine volumetric water content by subsampling soil column after removing probe or using weight 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 CS616/CS625 period output. When period 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 CS616/CS625 period value.

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 weight that can be put in oven or microwave. Weigh and record the wet soil weight.

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 weigh is constant.

Gravimetric water content is calculated after the container weight 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 weigh 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 CS616/CS625 period are one datum pair to be used for the calibration curve fit.

7.4 Collecting Field Data for Calibration

Required equipment

1. CS616/CS625 connected to datalogger programmed to measure probe output period

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 weight

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

Data needed for CS616/CS625 calibration are the CS616/CS625 output period (microseconds) and an independently determined volumetric water content. From this data, the probe response to changing water content can be described by a quadratic calibration equation of the form

$$\theta_v(\tau) = C_0 + C_1 * \tau + C_2 * \tau^2$$

with θ_v being the volumetric water content ($m^3\ m^{-3}$); τ , the CS616/CS625 period (microseconds); and C_n , the calibration coefficient (n = 0..2).

The linear form is

$$\theta_v(\tau) = C_0 + C_1 * \tau$$

with θ_v , the volumetric water content ($m^3\ m^{-3}$); τ, the CS616/CS625 period (microseconds); C_o , the intercept; and C_1 , the slope.

The calibration coefficients are derived from a curve fit of known water content and CS616/CS625 period.

The number of data sets needed to derive a calibration depends on whether the linear or quadratic form is being used and the accuracy requirement. Consider the expected range of soil water content while viewing FIGURE 2 and FIGURE 3. If the expected response is nearly linear, fewer laboratory measurements are needed to derive the calibration. A linear response is best described by data taken near the driest and wettest expected water contents.

Collecting measurements of CS616/CS625 period and core samples from the location where the probe is to be used will provide the best 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 CS616/CS625 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 CS616/CS625 output period to determine if the soil around the rods is at equilibrium.

With soil at equilibrium, record the CS616/CS625 period value.

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 CS616/CS625 should be inserted at least 3 times into the soil recording the period values following each insertion and using the average.

Remove the CS616/CS625 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 tray 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 weight that can be put in oven or microwave. Weigh and record the wet soil weight.

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 weigh is constant.

Gravimetric water content is calculated after the container weight 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 weight 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 CS616 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 weight 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 weight. This tray will hold the core sample during drying in an oven.

To obtain m_{wet}, subtract the cylinder empty weight and the container empty weight from the weight 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 weight 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

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

8. Maintenance

The CS616/CS625 does not require periodic maintenance.

9. References

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.

Rhoades, J.D., N.A. Manteghi, P.J. Shouse, W.J. Alves. 1989. Soil electrical conductivity and soil salinity: New formulations and calibrations. Soil Sci. Soc. Am. J., 53:433-439.

10. Appendix

10.1. 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}.

Notes: