

CS616 and CS625

Water Content
Reflectometers



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PLEASE READ FIRST

About this manual

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

Some useful conversion factors:

| | |
|--|---|
| Area: 1 in ² (square inch) = 645 mm ² | Mass: 1 oz. (ounce) = 28.35 g 1 lb (pound weight) = 0.454 kg |
| Length: 1 in. (inch) = 25.4 mm 1 ft (foot) = 304.8 mm 1 yard = 0.914 m 1 mile = 1.609 km | Pressure: 1 psi (lb/in ²) = 68.95 mb |
| | Volume: 1 UK pint = 568.3 ml 1 UK gallon = 4.546 litres 1 US gallon = 3.785 litres |

In addition, while most of the information in the manual is correct for all countries, certain information is specific to the North American market and so may not be applicable to European users.

Differences include the U.S standard external power supply details where some information (for example the AC transformer input voltage) will not be applicable for British/European use. *Please note, however, that when a power supply adapter is ordered it will be suitable for use in your country.*

Reference to some radio transmitters, digital cell phones and aerials may also not be applicable according to your locality.

Some brackets, shields and enclosure options, including wiring, are not sold as standard items in the European market; in some cases alternatives are offered. Details of the alternatives will be covered in separate manuals.

Part numbers prefixed with a “#” symbol are special order parts for use with non-EU variants or for special installations. Please quote the full part number with the # when ordering.

Recycling information



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Campbell Scientific Ltd can advise on the recycling of the equipment and in some cases arrange collection and the correct disposal of it, although charges may apply for some items or territories.

For further advice or support, please contact Campbell Scientific Ltd, or your local agent.



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Safety

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

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General

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

Utility and Electrical

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

Elevated Work and Weather

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

Maintenance

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

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CS616 and CS625 Water Content Reflectometers

1. Introduction

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 CR200(X)-series data loggers. The difference between the CS616 and the CS625 is the output voltage level.

Both water content reflectometers are designed to measure volumetric water content (VWC) 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.

NOTE

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

2. Precautions

- READ AND UNDERSTAND the *Safety* section at the front of this manual.
- Although the CS616/CS625 is rugged, it should be handled as precision scientific instrument.
- External RF sources can affect CS616/CS625 measurements. Consequently, the CS616/CS625 circuitry should be located away from significant sources of RF such as AC power lines and motors.
- CS616/CS625 probes enabled simultaneously and within approximately 23 cm (9 in) of each other can cause erratic measurements. If probes must be close to each other, configure the enable lines to the data logger control terminals so that the probes are not enabled simultaneously.

3. Initial Inspection

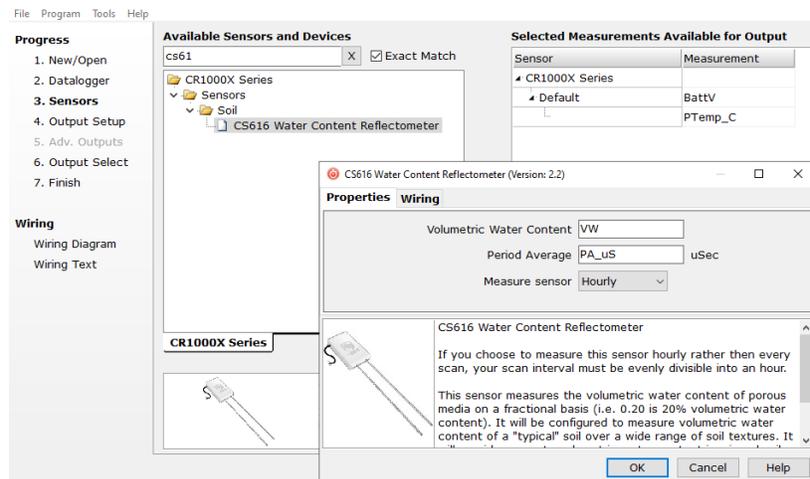
- Upon receipt of the CS616/CS625, inspect the packaging and contents for damage. File damage claims with the shipping company.
- The model number and cable length are printed on a label at the connection end of the cable. Check this information against the shipping documents to ensure the expected product and cable length are received.

4. QuickStart

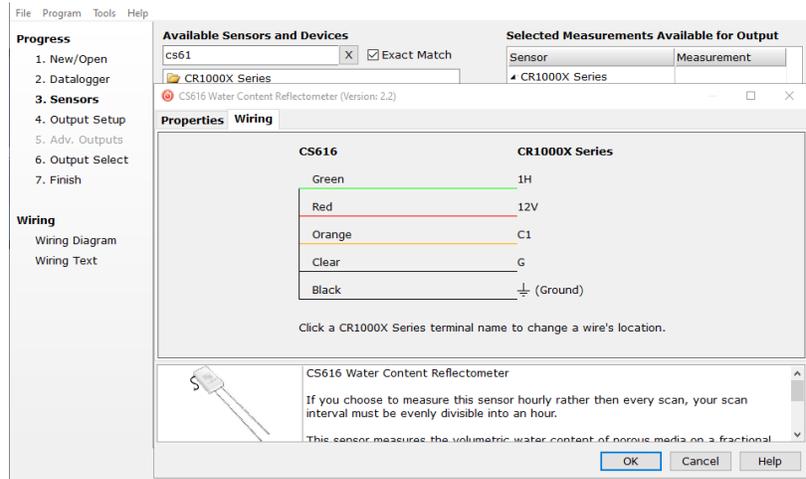
A video that describes data logger programming using *Short Cut* is available at: www.campbellsci.eu/videos/cr1000x-datalogger-getting-started-program-part-3. *Short Cut* is an easy way to program your data logger to measure the CS616 or CS625 probe and assign data logger wiring terminals. *Short Cut* is available as a download on www.campbellsci.eu. It is included in installations of *LoggerNet*, *RTDAQ*, *PC400*, or *PC200W*.

The following procedure also shows using *Short Cut* to program the CS616. The procedure for the CS625 is similar.

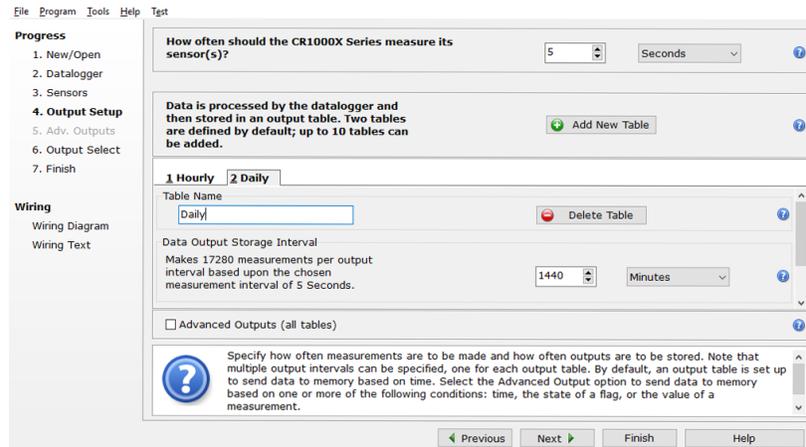
1. Open *Short Cut* and click **Create New Program**.
2. Double-click the data logger model.
3. In the **Available Sensors and Devices** box, type CS616 or locate the sensor in the **Sensors > Soil Moisture** folder. Double-click **CS616 Water Content Reflectometer**. It defaults to measuring the sensor hourly. This can be changed by clicking the **Measure Sensor** box and selecting **Every Scan**.



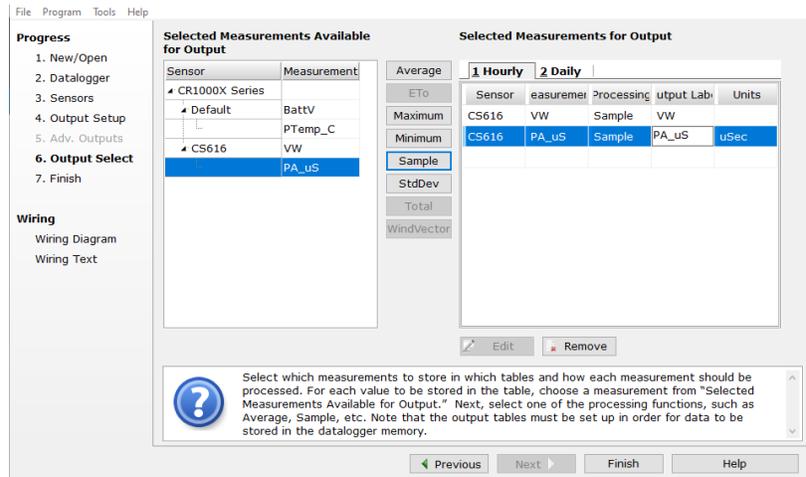
- Click the **Wiring** tab to see how the sensor is to be wired to the data logger. Click **OK** after wiring the sensor.



- Repeat steps 3 and 4 for other sensors.
- In **Output Setup**, type the scan rate, meaningful table names, and **Data Output Storage Interval**.



7. Select the measurement and its associated output option.



8. Click **Finish** and save the program. Send the program to the data logger if the data logger is connected to the computer.
9. If the sensor is connected to the data logger, check the output of the sensor in data display in *LoggerNet*, *RTDAQ*, *PC400*, or *PC200W* to make sure it is making reasonable measurements.

5. Overview

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 data logger. 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.

Features:

- High accuracy and high precision
- Fast response time
- Designed for long-term, unattended water content monitoring
- Probe rods can be inserted from the surface or buried at any orientation to the surface

- CS616 compatible with Campbell Scientific CRBasic data loggers: CR6, CR3000, CR1000X, CR800 series, and CR1000
- CS625 compatible with Campbell Scientific CRBasic data loggers: CR200X series and CR200 series

6. Specifications

| | |
|------------------------------------|---|
| Probe-to-Probe Variability: | $\pm 0.5\%$ VWC in dry soil, $\pm 1.5\%$ VWC in typical saturated soil |
| Resolution: | better than 0.1% VWC |
| Water Content Accuracy: | $\pm 2.5\%$ VWC using standard calibration with bulk electrical conductivity ≤ 0.5 deciSiemen per metre (dS/m) and bulk density ≤ 1.55 g/cm ³ in measurement range 0% to 50% VWC |
| Precision: | better than 0.1% VWC |
| Compliance documents: | View at www.campbellsci.eu/cs616-reflectometer |

6.1 Dimensions

| | |
|--------------------|--|
| Rods: | 300 mm (11.8 in) long, 3.2 mm (0.13 in) diameter, 32 mm (1.3 in) spacing |
| Probe Head: | 85 x 63 x 18 mm (3.3 x 2.5 x 0.7 in) |

6.2 Weight

| | |
|-------------------------------|---------------------------------------|
| Probe (without cable): | 280 g (9.9 oz) |
| Cable: | 35 g m ⁻¹ (0.38 oz per ft) |

6.3 Electrical Specifications

| | |
|-----------------------------------|--|
| Output | |
| CS616: | ± 0.7 volt square wave with frequency dependent on water content |
| CS625: | 0 to 3.3 volt square wave with frequency dependent on water content |
| Power: | 65 mA @ 12 VDC when enabled, 45 μ A quiescent |
| Power Supply Requirements: | 5 VDC minimum, 18 VDC maximum |
| Enable Voltage: | 4 VDC minimum, 18 VDC maximum |
| Maximum Cable Length: | 305 m (1000 ft) |

Electromagnetic Compatibility:

The CS616/CS625 is CE compliant with performance criteria available upon request. RF emissions are below EN55022 limits if the CS616/CS625 is enabled less than 0.6 ms and measurements are made at a 1 Hz (1 per second) or slower frequency. The CS616/CS625 meets EN61326 requirements for protection against electrostatic discharge and surge.

6.4 Operational Details

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.

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.

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

Soil Properties

The water content reflectometer operation can be affected when the signal applied to the probe rods is attenuated. The probe will respond 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. 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.

7. Installation

7.1 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.

7.2 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 the CS650G insertion guide tool. The CS650G is inserted into the soil and then removed. This makes proper installation of the water content reflectometer easier in dense or rocky soils.

7.3 Wiring

| TABLE 7-1. Data Logger/Reflectometer Wiring. | | |
|--|---------------|-----------------------------------|
| Colour | Function | Data Logger Connection |
| red | +12 V | +12 V |
| green | output | SE analogue or universal terminal |
| orange | enable | control terminal |
| black | signal ground | ⊕ |
| clear | power ground | G |

NOTE Both the black and clear wires must be grounded as shown in TABLE 7-1.

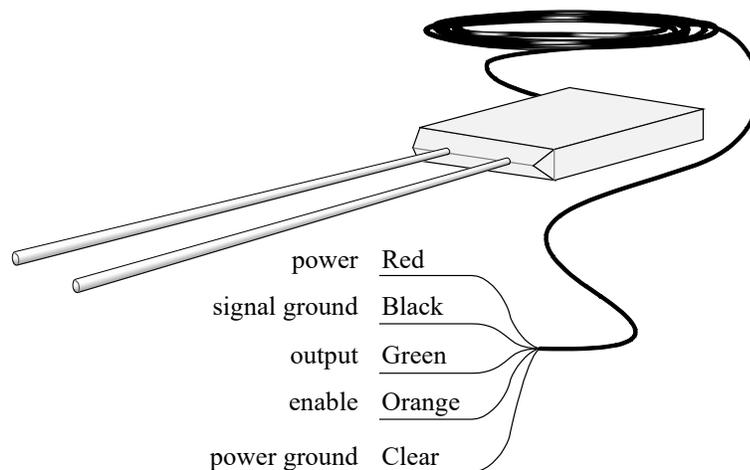


FIGURE 7-1. Water content reflectometer wires

7.4 Data Logger Programming

Short Cut is the best source for up-to-date data logger programming code.

If your data acquisition requirements are simple, you can probably create and maintain a data logger program exclusively with *Short Cut*. If your data acquisition needs are more complex, the files that *Short Cut* creates are a great

source for programming code to start a new program or add to an existing custom program.

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

A *Short Cut* tutorial is available in Section 4, *QuickStart* (p. 2). If you wish to import *Short Cut* code into *CRBasic Editor* to create or add to a customized program, follow the procedure in Appendix B, *Importing Short Cut Code Into CRBasic Editor* (p. B-1). Programming basics for CRBasic data loggers are provided here. Complete program examples for select CRBasic data loggers can be found in Appendix C, *Example Programs* (p. C-1). Programming basics and programming examples for Edlog data loggers are provided at www.campbellsci.com/old-manuals.

7.4.1 CS616 CRBasic Programming

The output of the CS616 is a square wave with amplitude of ± 0.7 VDC and a frequency that is dependent on the dielectric constant of the material surrounding the probe rods. The CRBasic instruction **CS616()** is used to measure the CS616 output period.

The **CS616()** CRBasic instruction has the following form.

CS616(Dest, Reps, SE, Control, MeasPerTerm, Mult, Offset)

Dest: The variable or variable array that stores the measurement results. *Dest* must be dimensioned to at least the number of *Reps*.

Reps: The number of measurements made using this instruction. If *Reps* is greater than 1, *Dest* must be an array dimensioned to the size of *Reps*.

SE: The single-ended terminal used to make the first measurement. If the *Reps* is greater than 1, additional measurements are made on sequential terminals.

Control: The control terminal used to enable the CS616 sensor.

MeasPerTerm: The number of control terminals used to control the CS616 sensor(s). If both *Reps* and *MeasPerTerm* are set to 4, the same control terminal will be used for all measurements. If *Reps* is set to 4 and *MeasPerTerm* is set to 1, four sequential terminals will be used for the measurements. If *Reps* is set to 4 and *MeasPerTerm* is set to 2, one control terminal will be used for the first two measurements, and the next terminal will be used for the next two measurements.

Mult, Offset: The *Mult* and *Offset* parameters are each a constant, variable, array, or expression by which to scale the results of the measurement.

7.4.2 CS625 CRBasic Programming

The output of the CS625 is a square wave with amplitude of 0 to 3.3 VDC 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(X) series data loggers 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.

The **PeriodAvg()** instruction has the following form.

`PeriodAvg(Dest, SE, Option, Cycles, Timeout, Control, Mult, Offset)`

Dest: The variable used to store the results of the measurement.

SE: The single-ended terminal to make the measurement. Valid options are analogue terminals 1 through 4.

Option: Specifies whether to output the frequency or the period of the signal. Code 0 returns the period of the signal in milliseconds.

Cycles: Specifies the number of cycles to average each scan.

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

Control: The control terminal or analogue terminal used to switch power to the CS625 Water Content Reflectometer.

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 1 is recommended.

8. Operation

8.1 Water Content Reflectometer Method for Measuring Volumetric Water Content

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 has a high value for dielectric permittivity and 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 two times the rod length is essentially measured.

The applied signal travels the length of the probe rods and is reflected from the rod ends travelling 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 data logger. The probe output

frequency or period is empirically related to water content using a calibration equation.

8.1.1 Response Curves

FIGURE 8-1 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 . For this soil, the saturation bulk electrical conductivity of 0.4 dS/m corresponds to laboratory electrical conductivity using extraction methods of about 2 dS/m .

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 $\pm 2.5\%$ volumetric water content for soil electrical conductivity $\leq 0.5 \text{ dS/m}$ and bulk density $\leq 1.55 \text{ g/cm}^3$ in a measurement range of 0% to 50% VWC.

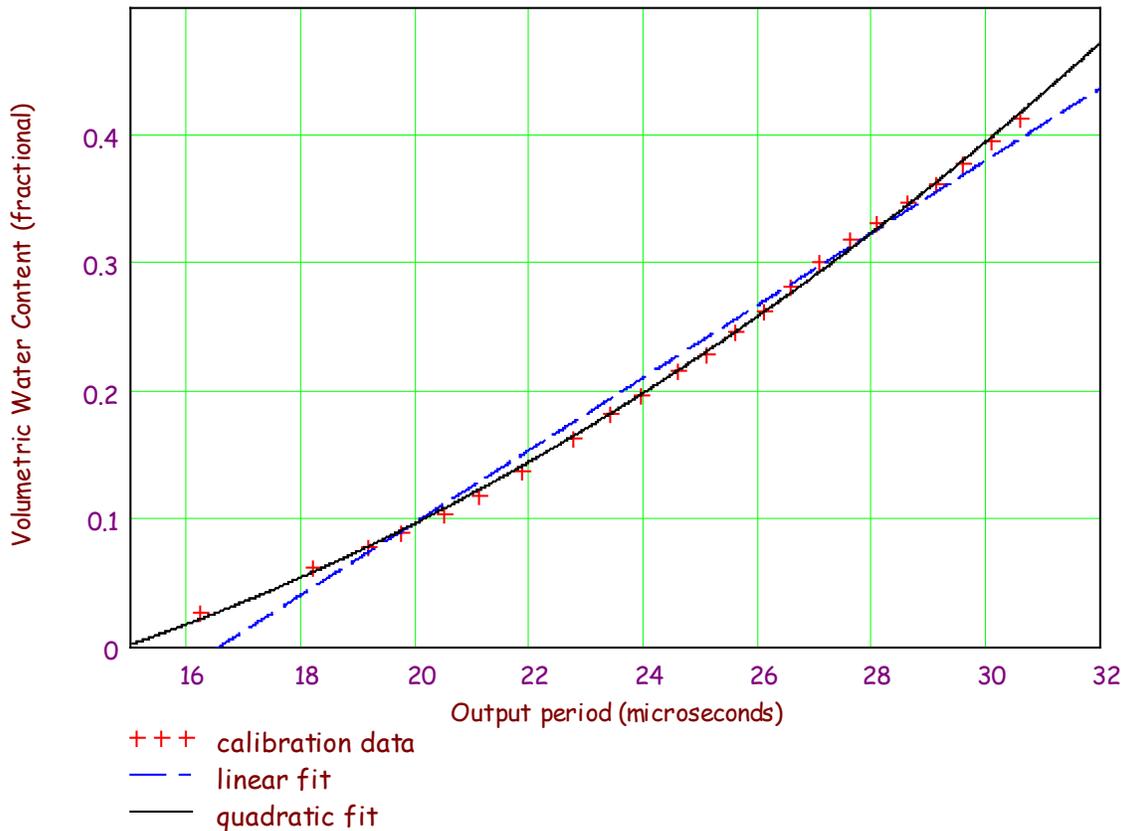


FIGURE 8-1. CS616 and CS625 linear and quadratic calibrations derived from loam soil

FIGURE 8-2 compares the CS616 response in the FIGURE 8-1 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 labelled *compacted soil* is 0.4 dS/m . The *compacted soil, high EC* had an electrical conductivity at saturation of 0.75 dS/m . The CS625 response is similar.

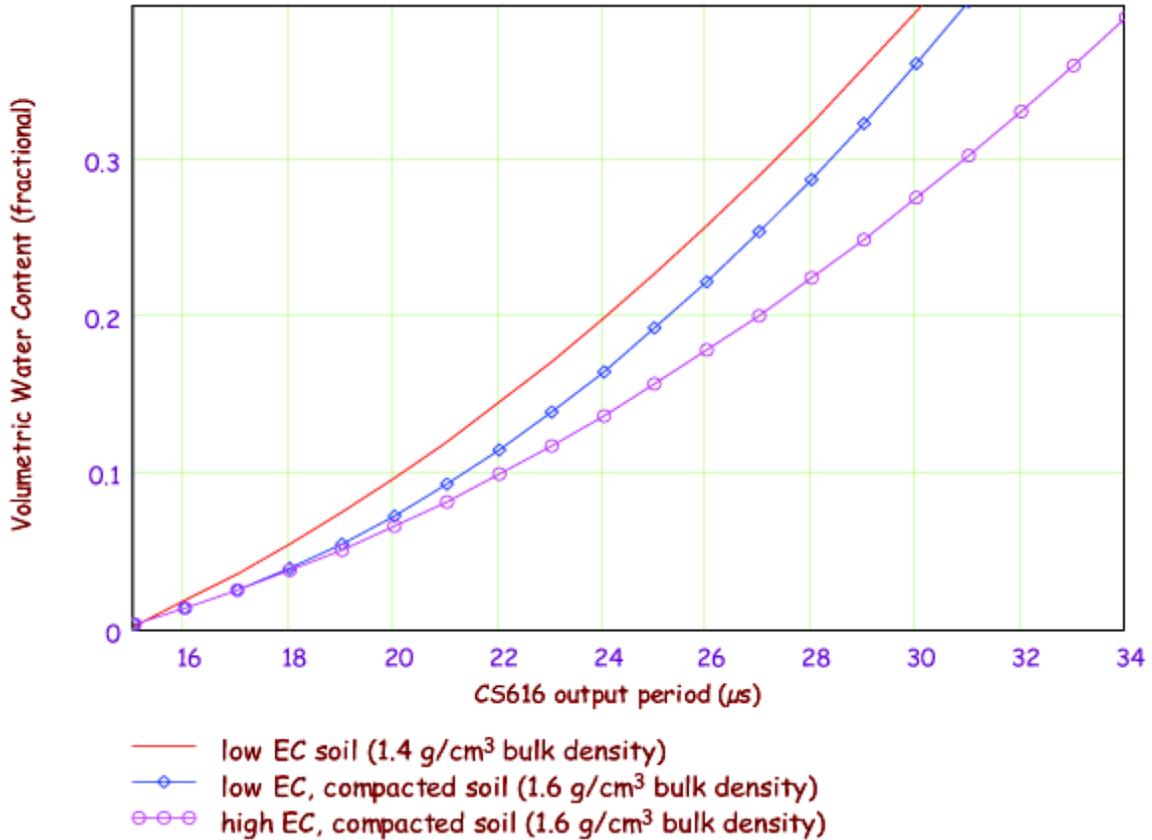


FIGURE 8-2. CS616 response for different soil types

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.

8.1.2 Calibration Equations

TABLE 8-1 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 , bulk density less than 1.55 g/cm^3 , and clay content less than 30%.

| TABLE 8-1. 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

$$\text{VWC} = -0.4677 + 0.0283 \times \text{period}$$

The quadratic equation is

$$\text{VWC} = -0.0663 - 0.0063 \times \text{period} + 0.0007 \times \text{period}^2$$

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 8-3 shows the difference between the linear and the quadratic calibration forms over the typical range. A CS616/CS625 output period of 16 microseconds is about 1.2% VWC and 32 microseconds is 44.9%. The linear calibration is within $\pm 2.7\%$ VWC of the quadratic. The linear calibration underestimates water content at the wet and dry ends of the range and overestimates it by up to about 2.6 % VWC at about 20% VWC.

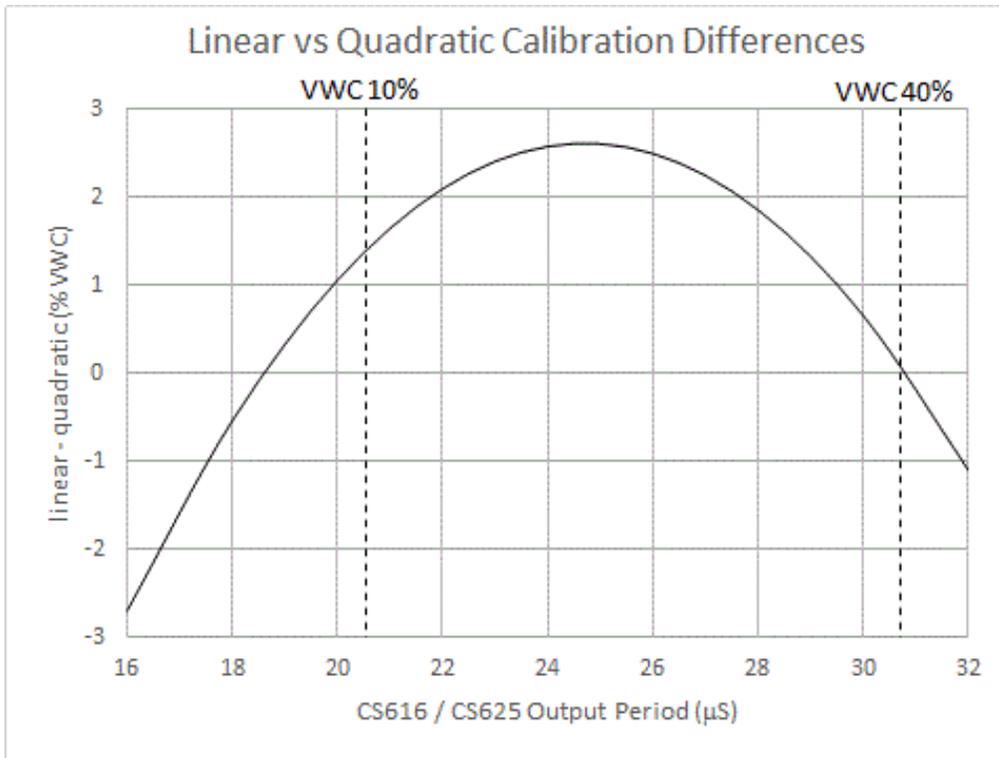


FIGURE 8-3. Linear versus quadratic calibration differences

The linear and quadratic coefficients for the sandy clay loam data in FIGURE 8-3 follow and can be used in similar soils.

| TABLE 8-2. Calibration coefficients for sandy clay loam with bulk density 1.6 g/cm³ and electrical conductivity at saturation 0.4 dS/m for both linear and quadratic forms. | | | | |
|---|-----------|------------------|-----------|-----------|
| Linear | | Quadratic | | |
| C0 | C1 | C0 | C1 | C2 |
| -0.6200 | 0.0329 | 0.0950 | -0.0211 | 0.0010 |

| TABLE 8-3. Calibration coefficients for sandy clay loam with bulk density 1.6 g/cm³ and electrical conductivity at saturation 0.75 dS/m for both linear and quadratic forms. | | | | |
|--|-----------|------------------|-----------|-----------|
| Linear | | Quadratic | | |
| C0 | C1 | C0 | C1 | C2 |
| -0.4470 | 0.0254 | -0.0180 | -0.0070 | 0.0006 |

8.1.3 Operating Range

8.1.3.1 Soil Electrical Conductivity

Electric conductivity can affect the propagation of electromagnetic fields used to configure the CS616/CS625. Free ions in soil solution provide electrical conduction paths that cause 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, σ_{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 following equation describes the relationship between soil solution and soil bulk electrical conductivity (Rhoades et al., 1976)

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

Where, σ_{bulk} is the electrical conductivity of the bulk soil; σ_{solution} , the soil solution; σ_{solid} , the solid constituents; θ_v , the volumetric water content; and T, a soil-specific transmission coefficient that accounts for the tortuosity of the flow path as water content changes. See Rhoades et al., 1989 for a form of this equation that accounts for mobile and immobile water. This publication also discusses soil properties related to CS616/CS625 operation such as clay content and compaction.

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. 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, the response of the CS616/CS625 output begins to change. The slope decreases with increasing electrical conductivity. Because of this, the calibration needs to be modified; see Appendix D, *Water Content Reflectometer User-Calibration (p. D-1)*. At electrical conductivity values greater than 5 dS/m, the probe output can become unstable.

8.1.3.2 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 re-orientate or polarize the water molecules. If other forces are acting on the polar water molecules, the force exerted by the applied signal are less likely to polarize the molecules. This causes the probe to under report water content. Additionally, some clays absorb 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 can cause the probe to over report water content. It would be convenient if the calibration of water content to CS616/CS625 output period could be adjusted according to some soil parameter that reflects the character of the signal attenuation. However, such a parameter has not been identified.

For some soils with bulk densities exceeding 1.5 g/cm³, the slope of the CS616/CS625 response decreases with increasing bulk density.

8.1.4 Error Sources in Water Content Reflectometer Measurement

8.1.4.1 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 $\pm 2\%$ volumetric water content.

8.1.4.2 Insertion Error

The method used for probe insertion can affect the accuracy of the measurement. Keep the probe rods 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 CS650G insertion tool.

8.1.4.3 Signal Attenuation Error

Section 8.1, *Water Content Reflectometer Method for Measuring Volumetric Water Content* (p. 9), 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 bulk electrical conductivity. Between 0.5 dS/m and 5 dS/m, the CS616/CS625 will continue to give a well-behaved response to changes in water content but a soil specific calibration is required. See Appendix D, *Water Content Reflectometer User-Calibration* (p. D-1), for calibration information.

8.1.5 Temperature Dependence and Correction

FIGURE 8-4 shows the error in measured volumetric water content caused by the temperature dependence of the CS616/CS625. 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 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, $\tau_{\text{uncorrected}}$, to 20 °C knowing the soil temperature, T_{soil} . See Appendix C.2.2, *CR200(X) Program with Temperature Correction* (p. C-6). The temperature correction assumes that both the water content and temperature do not vary over the length of the probes rods.

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

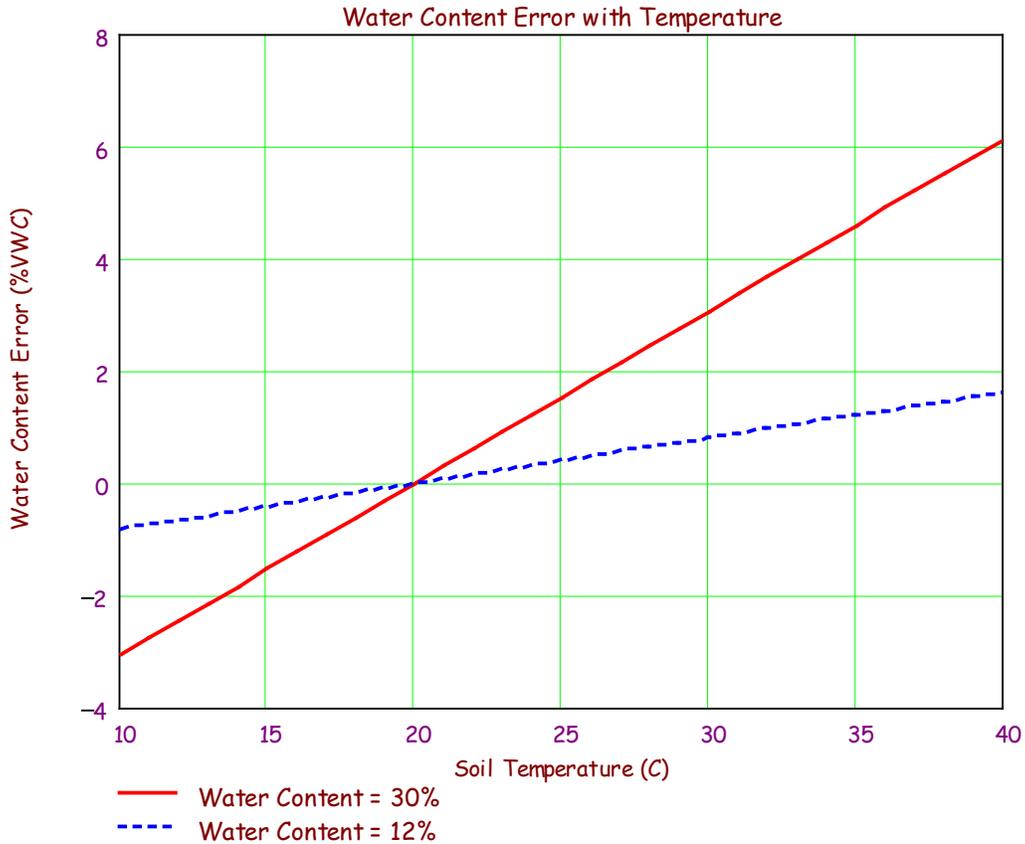


FIGURE 8-4. Percent volumetric water content error adjusted with temperature correction equation

9. Maintenance

The CS616/CS625 does not require periodic maintenance.

10. 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.

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 (θ_g) is the mass of water per mass of dry soil. It is measured by weighing a soil sample (m_{wet}), drying the sample to remove the water, then weighing the dried soil (m_{dry}).

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

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:

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

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.

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

The term ρ_{solid} is the density of the soil solid fraction and is approximately 2.65 g/cm³.

Appendix B. Importing Short Cut Code Into CRBasic Editor

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

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

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

NOTE

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

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

Appendix C. Example Programs

C.1 CS616 Programs

C.1.1 CR1000X Program for Measuring Eight CS616 Probes

The following CR1000X program uses the CS616() instruction to measure eight CS616 probes connected to the CR1000X data logger (TABLE C-1). Although this example is for the CR1000X, other CRBasic data loggers are programmed similarly.

| Probe Number | Green | Orange | Red | Black | Clear |
|---------------------|--------------|---------------|------------|--------------|--------------|
| CS616 #1 | 5H | C7 | 12V | ⊥ | G |
| CS616 #2 | 5L | C7 | 12V | ⊥ | G |
| CS616 #3 | 6H | C7 | 12V | ⊥ | G |
| CS616 #4 | 6L | C7 | 12V | ⊥ | G |
| CS616 #5 | 7H | C8 | 12V | ⊥ | G |
| CS616 #6 | 7L | C8 | 12V | ⊥ | G |
| CS616 #7 | 8H | C8 | 12V | ⊥ | G |
| CS616 #8 | 8L | C8 | 12V | ⊥ | G |

Note: The red wire for all eight CS616s connect to the 12V terminal. A user-supplied common tie post may be required.

CRBasic Example C-1. CR1000X Program for Measuring Eight CS616 Probes

```

'Declare Public and Dim Variables
Public batt_volt
Public Panel_temp
Public Period (8)
Public VWC (8)
Public Flag (1)
Dim I

'Declare Constants
'CS616 Default Calibration Constants
const a0= -0.0663
const a1= -0.0063
const a2= 0.0007
'Flag logic constants
const high = true
const low = false

'Define Data Tables
DataTable (Dat30min,1,-1)
  DataInterval (0,30,Min,10)
  Minimum (1,batt_volt,IEEE4,0,False)
  Average (1,Panel_temp,IEEE4,0)
  Sample (8,Period(),FP2)
  Sample (8,VWC(),FP2)
EndTable

'Main Program
BeginProg
  Scan (5,Sec,0,0) 'scan instructions every 5 sec
  Battery (Batt_volt)
  PanelTemp (Panel_temp,250)
  '
  'Set flag 1 High every 30 min (Note: User can manually set flag 1 high/low)
  If IfTime (0,30,min) Then flag (1) = high '+++++
  If Flag (1) = high Then
    'measure 8ea CS616 probes on CR1000X
    CS616 (Period(1),4,9,C7,4,1.0,0) 'measure 4ea CS616 probes, enable w/ C7
    CS616 (Period(5),4,13,C8,4,1.0,0) 'measure 4ea CS616 probes, enable w/ C8
    '
    For I=1 to 8 'convert CS616 period to Volumetric Water Content
      VWC(I)=a0 + a1*Period(I) + a2*Period(I)^2
    Next
    '
    flag(1)= low 'set Flag 1 = Low
    '
  EndIf '+++++
  '
  CallTable Dat30min 'Call Output Tables
NextScan
EndProg

```

C.1.2 CR1000X/Multiplexer Program for Measuring 48 CS616 Probes

The following program uses the AM16/32-series multiplexer to measure 48 CS616 probes connected in the 4x16 configuration; wiring is provided in TABLE C-2). The program also measures data logger battery voltage and temperature.

| TABLE C-2. Wiring for CR1000X/Multiplexer Example | | | |
|--|------------------------------|-------------------------|--------------------------|
| CR1000X | AM16/32-series (4x16) | | CS616¹ |
| | Control/Common | Sensor Terminals | |
| C4 | RES | Odd H | CS616#1_Green |
| C5 | CLK | Odd L | CS616#2_Green |
| 12 V | 12 V | G | #1,2,3_Black & Clear |
| Gnd | Gnd | Even H | CS616#3_Green |
| 1H | COM Odd H | Even L | CS616 #1,2,3_Orange |
| 1L | COM Odd L | | |
| Gnd | Gnd | | |
| 2H | COM Even H | | |
| C6 | COM Even L | | |

¹Three sensors to each set of AM16/32 terminals.

CRBasic Example C-2. CR1000X/Multiplexer Program for Measuring 48 CS616 Probes

```

'Declare Public and Dim Variables
Public batt_volt
Public Panel_temp
Public Period (48)
Public VWC (48)
Public Flag (1)
Dim I

'Declare Constants
'CS616 Default Calibration Constants
const a0= -0.0663
const a1= -0.0063
const a2= 0.0007
'Flag logic constants
const high = true
const low = false

'Define Data Tables
DataTable (Dat30min,1,-1)
  DataInterval (0,30,Min,10)
  Minimum (1,batt_volt,FP2,0,False)
  Average (1,Panel_temp,FP2,0)
  Sample (48,Period(),FP2)
  Sample (48,VWC(),FP2)
EndTable

'Main Program
BeginProg
  Scan (5,Sec,0,0)          'scan instructions every 5 sec
  Battery (Batt_volt)
  PanelTemp (Panel_temp,250)
  '
  'Set flag 1 High every 30 min (Note: User can manually set flag 1 high/low)
  IF IFTIME (0,30,min) THEN flag (1) = high '+++++
  IF Flag (1) = high THEN
    'measure 48ea CS616 probes on AM16/32 in (4x16) mode
    PortSet (C4,1)          'Set Mux Reset line High
    '
    I=1                      'Set sub scan loop counter
    SubScan (0,mSec,16)
      PulsePort (C5,10000)  'Clock Mux
      CS616 (Period(I),3,1,C6,3,1.0,0) 'Measure 3ea CS616 probes
      I=I+3
    NextSubScan
  '
  For I=1 to 48              'convert CS616 period to Volumetric Water Content
    VWC(I)=a0 + a1*Period(I) + a2*Period(I)^2
  Next
  '
  PortSet (C4,0)            'Set Mux Reset line Low
  flag (1) = low
  '
  EndIf                      '+++++
  '
  CallTable Dat30min        'Call Output Tables
NextScan
EndProg

```

C.2 CS625 Programs

C.2.1 CR200(X) Program for Measuring Four CS625 Probes

This CR200X program measures volumetric water content with four CS625 probes; TABLE C-3 provides wiring. The average hourly readings are saved in final storage every 4 hours.

| Wire Colour | CR200(X) |
|-------------|-----------------|
| Green | SE1 through SE4 |
| Black | G |
| Orange | C1 |
| Red | SW Battery |
| Clear | G |

CRBasic Example C-3. CR200(X) Program for Measuring Four CS625 Probes

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

'Declare Variables
Public 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 (4,vwc,0)
EndTable

'Main Program

BeginProg
Scan (1,hr)
SWBatt (1)
PeriodAvg (period(1),1,0,10,10,C1,1,0)
PeriodAvg (period(2),2,0,10,10,C1,1,0)
PeriodAvg (period(3),3,0,10,10,C1,1,0)
PeriodAvg (period(4),4,0,10,10,C1,1,0)
For i=1 To 4
vwc(i) = a0 + a1*period(i) + a2*period(i)^2
Next i

CallTable ofile
NextScan
EndProg
```

C.2.2 CR200(X) Program with Temperature Correction

This CR200X program measures temperature with 109 probe and uses the 109 temperature to correct the period for one CS625. The standard calibration equation is used 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. Wiring for the CS625 is provided in TABLE C-4 and wiring for the 109 is provided in TABLE C-5.

| TABLE C-4. CS625 Wiring for CR200X Program with Temperature Correction | |
|---|-----------------|
| CS625 | CR200(X) |
| Green | SE1 |
| Black | G |
| Orange | C1 |
| Red | SW Battery |
| Clear | G |

| TABLE C-5. 109 Wiring for CR200X Program with Temperature Correction | |
|---|-----------------|
| 109 | CR200(X) |
| Black | EX1 |
| Red | SE5 |
| Purple | G |
| Clear | G |

CRBasic Example C-4. CR200(X) Program with Temperature Correction

```

'CR200(X) program to read one 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

```


Appendix D. Water Content Reflectometer User-Calibration

D.1 Signal Attenuation in Conductive Soils and Need for Site-Specific Calibration

The calibration equations in Section 8.1.2, *Calibration Equations (p. 11)*, provide accurate volumetric water content over a wide range of mineral soils. For soils with higher electrical conductivity or higher bulk density, however, those equations overestimate volumetric water content and a soil specific user-calibration is recommended. Perform a soil specific calibration if the soil where the CS616 is to be buried has one or more of the following characteristics:

- Saturated bulk electrical conductivity is greater than 0.5 dS/m
- Smectite clay content is greater than 25%
- Non-smectite clay content is greater than 30%
- Organic matter content is greater than 5%
- Bulk density is greater than 1.55 g/cm³

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.

D.2 User-Derived Calibration Equation

The probe output response to changing water content is nonlinear. It is well described by a quadratic or a logarithmic form.

Quadratic form:

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

Logarithmic form:

$$\theta_v(\tau) = C_0 + C_1 \times \tau^2 \times \ln(\tau)$$

Where: θ_v = volumetric water content (m³ m⁻³)

τ = CS616 period (microseconds)

C_n , = calibration coefficient (n = 0, 1, or 2)

The standard calibration coefficients were derived from factory laboratory measurements using curve fitting of known volumetric water content to probe output period. TABLE D-1 shows the calibration coefficients for the standard quadratic equation and its equivalent logarithmic equation.

| Quadratic | | | Logarithmic | |
|------------------|---------|--------|--------------------|----------|
| C_0 | C_1 | C_2 | C_0 | C_1 |
| -0.0663 | -0.0063 | 0.0007 | -0.0957 | 0.000153 |

The purpose of the user-derived calibration procedure is to determine better values for C_n for the soil where the CS616 is buried.

Two data points from careful measurements can be enough to derive the logarithmic calibration. A minimum of three data points, gathered at approximately evenly spaced water contents covering the expected range, is needed for a quadratic calibration.

The calibration function describing the CS616 response to changing water content is always concave up. Calibration data that suggests a different shape indicates a problem with the data or method.

Collect the calibration data using either a laboratory method or a field method. Use the laboratory method if the sensors are not installed in the soil of interest. If the sensors are installed and the volumetric water content readings seem too high, use the field method to avoid removing the sensors.

D.3 Collecting Laboratory Data for Calibration

D.3.1 Equipment needed

Soil Collection:

- Shovel
- Bucket or bag large enough to hold at least 2.7 kg (6 lb) of soil
- Volumetric soil sampler
- Plastic bags
- Marker
- Insulated container for holding soil samples

Soil Preparation:

- Plastic sheet for air drying soil

D.3.2 Soil Preparation

From pp 468 – 469 Methods of Soil Analysis, section 3.1.3.6 “Capacitance Devices” Starr & Paltineanu:

1. Choose a container size and shape to accommodate the sensor’s primary zone of influence.
2. Screen the required mass of soil through a 5-mm sieve.
3. Air-dry and thoroughly mix the soil.

4. Choose the volumetric soil water content range and at least four water content increments for the calibration curve.
5. Weigh the desired mass of soil for a 2-cm soil depth to be packed to the chosen soil density.
6. Carefully pack the soil to the desired bulk density.
7. Repeat steps 5-6 until container is filled with soil.
8. Push the probe rods into the soil without creating air-gaps along the rods.
9. Record probe reading in the container.
10. Remove the probe and record total soil mass in the container.
11. Subsample the soil for wet and dry weights and calculate wet and dry densities and VWC. Collect samples from around and close to the rods for oven drying.
12. Prepare the soil for the next calibration point by spreading the soil out in a thin layer on a plastic sheet; then mist-spray the measured volume of water on the soil in several increments, mixing the soil between each increment by pulling first one corner of the plastic sheet toward the opposite corner and then the other corners.
13. Repeat steps 5 to 12 for each calibration point.
14. Determine calibration equation by regression analysis with appropriate functional relationship.

CS616/CS625 calibration uses 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 the following quadratic calibration equation:

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

Where: θ_v = volumetric water content ($\text{m}^3 \text{m}^{-3}$)
 τ = CS616 period (microseconds)
 C_n , = calibration coefficient (n = 0, 1, or 2)

The linear calibration equation is:

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

Where: θ_v = volumetric water content ($\text{m}^3 \text{m}^{-3}$)
 τ = CS616 period (microseconds)
 C_0 = intercept
 C_1 = slope

Required equipment:

- CS616/CS625 connected to data logger programmed to measure output period
- Cylindrical sampling devices to determine sample volume for bulk density; for example, copper tubing with diameter ≥ 2.5 cm (1 in) and length about 5 cm (2 in)
- Containers and scale to measure soil sample weight
- 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 using the linear or quadratic form and the accuracy requirement. Consider the expected range of soil water content while viewing FIGURE 8-1 and FIGURE 8-2. 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. Ensure only soil is in the region within 5 cm of the rod surface. Bury the probe rods 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 to 1.4 g/cm³. This is especially important when bulk density is greater than 1.55 g/cm³. 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.

Use a container that is large enough to allow the probe rods to be at least at least 10 cm (4 in) away from the container surface.

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

Either bury the probe rods in a tray or insert them into a column. When using a column, carefully insert the rods until the rods are completely surrounded by soil. Avoid moving rods from side-to-side because this can form air voids around rod surface, a source of measurement errors.

Collect the probe output period. Repeat the previous step and this step three to four times.

Determine the volumetric water content by subsampling soil column after removing the probe or by using the column weight. If subsampling is used, remove soil from column and remix with samples used for water content measurement. Repack column then add water to the top of the container.

Allow the column 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. Verify equilibration by frequently observing the CS616/CS625 period output. When the 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. Use copper tubing with a diameter ≥ 2.5 cm (1 in) and length about 5 cm (2 in). The tubes can be pressed into the soil surface.

Take multiple samples. Three carefully handled samples will provide good results.

Evenly push the sample tubes 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 the tube to a tray or container of known weight that can be put in oven or microwave. Weigh and record the wet soil weight.

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

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

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

For the bulk density, the dry weigh of the sample is divided by the sample tube volume.

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

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

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

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.

D.4 Collecting Field Data for Calibration

Required equipment:

- CS616/CS625 connected to data logger programmed to measure probe output period
- Cylindrical sampling devices to determine sample volume for bulk density such as copper tubing with diameter ≥ 2.5 cm (1 in) and length about 2.5 cm (1 in)
- Containers and scale to measure soil sample weight
- Oven or microwave to dry samples

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

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

Where: θ_v = volumetric water content ($\text{m}^3 \text{m}^{-3}$)
 τ = CS616 period (microseconds)
 C_n = calibration coefficient ($n = 0, 1, \text{ or } 2$)

The linear form is:

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

Where: θ_v = volumetric water content ($\text{m}^3 \text{m}^{-3}$)
 τ = CS616 period (microseconds)
 C_0 = intercept
 C_1 = 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 8-1 and FIGURE 8-2. 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.

Use a shovel to form a vertical face of soil. If the CS616/CS625 is to be used within about 0.5 m (1.5 ft) 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 when 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. Use the average of several core samples 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. Use copper tubing with a diameter ≥ 2.5 cm (1 in) and length about 5 cm (2 in). The tubes can be pressed into the soil surface. It is good to take replicate samples at locations around the tray surface.

Take three carefully handled samples at locations around the tray surface.

Evenly push the sample tubes into the soil surface. Remove the tube and sample and gently trim the ends of excess soil. Remove excess soil from the outside of the 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.

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

Calculate gravimetric water content after accounting for the container weight.

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

For the bulk density, the dry weight of the sample is divided by the sample tube volume.

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

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

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

The average water content for the replicates and the recorded CS616 period are one datum pair to be used for the calibration curve fit.

D.5 Calculations

Clean the empty cylinders used for core sampling. Measure and record the empty weight and volume. For a cylinder, the volume is:

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

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.

After obtaining soil core samples, place the soil-filled cylinder in a small tray of known empty weight. This tray will hold the core sample during oven drying.

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 in Appendix D.4, *Collecting Field Data for Calibration* (p. D-6).

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

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

Use the following to calculate volumetric water content:

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



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