Center for Urban Environmental Research and Education
University of Maryland, Baltimore County

Methodology for Installation of Soil Heat Flux Plates, Soil Thermocouples, Water Content Reflectometers, Soil Moisture Probes and Soil Matric Potential Probes

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ON THE COVER
Final Installation of Soil Sensors: November 19, 2008. Photograph by Christiane Runyan.

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1. Introduction

The objectives of the UMBC/CUERE installation are: (1) to provide soil energy balance data required for eddy flux measurements (soil heat flux (Hukseflux HFP01), soil temperature (Campbell Scientific, Inc. TCAV) and soil moisture (Campbell Scientific, Inc. CS 616)), and (2) to test a system of soil sensors for the purpose of measuring soil moisture (Decagon Devices, Inc. EC-TM), soil temperature (Decagon Devices, Inc. EC-TM) and soil matric potential (Decagon Devices, Inc. MPS-1), and these parameter's variability at 10, 50, and 100 cm depths. Sensor deployment at these depths were chosen because these are among the standard depths used to measure soil parameters for soil research and for Soil Climate Analysis Network sites (USDA, 2009). The soil sensors required for eddy flux measurements were deployed at depths suggested by the Campbell Scientific, Inc. TCAV Averaging Soil Thermocouple Probe Instruction Manual. Lessons learned from this test can be used to design and optimize a spatial network of soil sensors measuring soil moisture, soil temperature, soil matric potential in the Gwynn's Falls watershed with respect to the type of sensor used, the number of sensors per network node and the measurement depths of the soil parameters.

2. Principles of Operation

2.1 Soil Heat Flux Plate

The soil heat flux plate uses a thermopile to measure passive thermal energy gradients across the plate. It generates a small output voltage (the signal) proportional to the differential temperature (local heat flux). When heat flows through the sensor, the filling material acts as a resistance and heat flow occurs along a warm to cool gradient (Campbell Scientific, Inc., 2007). The heat flux plates are used in combination with the soil thermocouples, which measure the temporal change in temperature in the soil layer, and the CS616 water content reflectometers, which measure the volumetric water content (VWC) of the soil.

2.2 Soil Thermocouple

A soil thermocouple probe measures temperature at four locations, or junctions, each consisting of a type E thermocouple wire (chromel-constantan) that is enclosed within a stainless steel tube (Campbell Scientific, Inc., 1990). These four thermocouple junctions measure soil temperature independently and are connected in parallel to one datalogger channel (Campbell Scientific, Inc., 1990). When a measurement instruction is sent from the datalogger, the channel measures the output voltage of the soil thermocouple probe, which is the average of these four junctions' temperature measurement (Campbell Scientific, Inc., 1990).

2.3 Water Content Reflectometer

The Campbell Scientific water content reflectometers (CS616) indirectly measure the volumetric water content of soil by using electromagnetic (EM) wave propagation to measure the soil's dielectric permittivity (Campbell Scientific, Inc., 2006). Dielectric permittivity is a measure of a soil's ability to store or transmit an electrical charge and is proportional to soil moisture content (Decagon Devices, Inc., 2009). The CS616 consists of two stainless steel rods, or wave guides, that are inserted into the soil. The CS616 circuit board emits an electromagnetic pulse, or wave, along the wave guides and measures the time difference between the sent pulse and the reflected pulse (wave propagation), which is created when the sent pulse reaches the end of the rods (Campbell Scientific, Inc., 2006). The velocity of the electromagnetic pulse is inversely proportional to the dielectric permittivity and moisture content of the soil surrounding the rods (Campbell Scientific, Inc., 2006).

2.4 ECH2O-TM

The Decagon ECH2O-TM sensor measures water content and temperature of the soil. A 70 MHz oscillating electromagnetic wave is supplied by the probe to probe prongs that store a charge proportional to soil dielectric and soil volumetric water content (Decagon Devices, Inc., 2007). A thermistor in thermal contact with the probe prongs provides an average prong temperature. The output of the probe is in degrees Celsius. If the black plastic overmold is exposed to direct sunlight, techniques to reduce radiation load need to be used. Soil moisture measurements from the ECH2O-TM can be temperature-corrected using soil temperature through the following equation, where C1-C3 are coefficients determined from a multiple regression of field data (Cobos and Campbell, 2007):

$$VWC_{corrected} = C1 * VWC_{meas} + C2 * T_{soil} + C3 \tag{1}$$

where

$VWC_{corrected}$ is corrected volumetric water content
VWC_{meas} is measured volumetric water content
T_{soil} is measured soil temperature in degrees Celsius
C1, C2, C3 are multiple regression coefficients

Decagon states that the factory-provided calibration can be used to obtain an accuracy of +/-3% in mineral soils, although this accuracy is lower in soils >53% clay or >79% sand (Campbell et al., 2007). According to Decagon, a soil-specific calibration can improve accuracy to 1-2% of the total error (Decagon Devices, Inc., 2007). Probes are identical in construction therefore a soil-specific calibration obtained using one probe can be applied to other probes in the same soil (Campbell et al., 2007).

2.5 MPS-1

The Decagon MPS-1 measures soil water potential, which is the energy state of water in soil that aids to describe how water will move within soil (Decagon Devices, Inc., 2008). All soil water potential measurement techniques measure the potential energy of water in equilibrium with water in the soil because the Second Law of Thermodynamics states that connected systems with differing energy levels will move towards an equilibrium energy level (Decagon Devices, Inc., 2008). Thus, if an object comes into hydraulic contact with the soil, the water potential of the object will come into equilibrium with the soil water potential (Decagon Devices, Inc., 2008).

When placed in the soil, the MPS-1 contains a ceramic disk with a static matrix of pores that comes into hydraulic equilibrium with the soil. Soil water potential is then measured by measuring the water content of the ceramic disk. The disk's water content is related to the water potential in the disk by a relationship defined by the Decagon-derived calibration formula that is automatically applied to the sensor output. MPS-1 and their calibration formulas are not sensitive to soil type (Decagon Devices, Inc., 2008).

The MPS-1 is less accurate (±20%) and less precise (4 kPa) at high water potential (50 to 500kPa), but is often preferred to the more accurate tensiometers. MPS-1 are advantageous to tensiometers because they require little to no maintenance, have a larger measurement range and their ceramic disks are unaffected by freezing conditions, which allows them to remain field deployed all year. The MPS-1 cannot measure soil water potential in frozen soils, but soil water potential can be indirectly measured with soil temperature. For soil water potential less than -50 kPa, the soil water potential decreases by about 1200 kPa for each 1°C decrease below 0°C (Decagon Devices, Inc., 2008).

3. Programming

3.1 Loggernet

In order for a datalogger to record data, a program must be written and uploaded to the datalogger. The program can be written for the Campbell Scientific CR1000 and CR5000 dataloggers using Campbell Scientific's "Loggernet" application: CRBasic or Shortcut. Loggernet is also used to communicate with and upload the program to the datalogger.

3.2 Calibration Values

The only soil sensors that have a unique calibration value are the soil heat flux plates. The unique factory calibration values for the individual soil heat flux plates need to be entered into the datalogger program that is used to make measurements. The calibration value provides the value required to convert voltage to heat flux by dividing millivolt output by the heat flux plate calibration constant.

3.3 Soil Thermocouples

The program for the thermocouple measurement should be written so that it uses a differential voltage measurement to obtain a temperature measurement, which aids in reducing noise and ground loop problems (Campbell Scientific, Inc, 1990).

4. Wiring

The user should wire all sensors to the datalogger in accordance with the Soil2b.CR1 program wiring description (Figure 1). Appendix A provides a sample wiring description. An external battery/power source will need to be supplied for testing and deployment purposes.

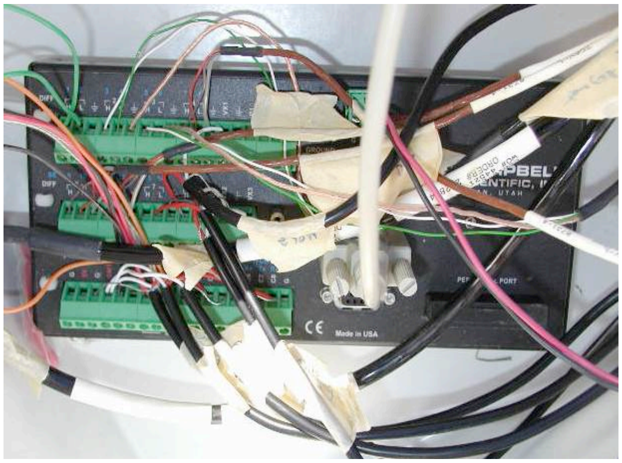


Figure 1. CR1000 wiring scheme for soil sensors.

4.1 MPS-1

The MPS-1 wires should be connected to the datalogger as follows. The supply wire (white) must be connected to the "Switched Voltage Excitation (VX)", the analog output wire (red) to a single ended channel (analog input), and the bare ground wire to the ground. "Switched Voltage Excitation" provides precision programmable voltages within ±2.5 Volt range for bridge measurements (Campbell Scientific, Inc., 2006). A bridge measurement is obtained from a system within a sensor of two or more resistors wired in series that change resistance based upon some change in a physical property (Campbell Scientific, Australia, 2009). The program function used to initiate an MPS-1 measurement, BrHalf, can only control a maximum of two MPS-1 sensors per excitation channel; the program and wiring description therefore should be adjusted for the number of sensors.

4.2 ECH2O

The ECH2O sensors must be wired to the CR1000 datalogger with all white (excitation) wires connected to the Switched (SW) 12 V power supply terminal on the datalogger, red wires connected to individual control ports on the datalogger and bare wires connected to a ground on the datalogger. The Switched 12 Volts SW-12 terminals on the Campbell Scientific CR1000 and CR5000 dataloggers provide an unregulated 12 volts that can be switched on and off under program control (Campbell Scientific, Inc., 2006). In addition, if using a Campbell Scientific datalogger (e.g., the CR1000 or the CR5000), a 200 ohm resistor must be added between the 12 V power terminal and the excitation wire (white) on the sensors. This can be done by soldering the wires together. This is due to a post-production problem with the sensors that causes fluctuations within the data output.

Although the example program in the Decagon manual states that a jumper cable is needed between C3 and SW12V (Power Out) this is not necessary because it causes the circuit to short (Decagon Technical Support, telephone communication, November 2008).

5. Preparation for Field Deployment

5.1 Bulk Density and Volumetric Water Content (VWC) Measurements

Soil bulk density is required if using the ECH2O site-specific calibration, for computing the initial VWC and for many soil computations. The soil's VWC is obtained when measuring bulk density and can be compared to sensor VWC (using its factory calibration) if the sensor is installed promptly after sampling. The following numbered steps can be used to obtain a bulk density measurement (for additional resources see Starr and Palineanu (2002), Decagon Application Guide).

Figure 2. Bulk density core sampler made from ½" electrical conduit.

1. Dry the drying container in a desiccator for 24 hours.
2. Weigh and record the drying container's tare weight to the nearest 0.01g.
3. Take three samples of soil from desired depths using a bulk density core sampler of known volume while being careful not to compact soil cores (Figure 2). A caliper can be used to determine the diameter and height of the bulk density sampler.
4. Evenly trim both ends of the soil core sampler. Repack soil at the estimated field bulk density into voids that are created when trimming the soil core or removing the sampler from the pit wall.
5. Remove all the soil from the sampler and place into the weighed drying container. Weigh and record the soil and container to the nearest 0.01g.
6. Place the sample (in the container) in an oven at 110˚ C for 24 hours if the soil is less than 3% organic matter. If the soil is high in volatile organics, then place the soil in the oven at 60-70˚C for 48 hours (Cobos et al., 2008). Use soil color as an indicator of organic matter content but if

the organic content of the soil is unknown, dry the sample at 60-70 ˚C for 48 hours, weigh and record. Then dry at 110˚C for 24 hours, weigh and record. Compute the percent organic matter (%OM) (Dane, 2002).

7. Weigh and record the weight of the container and dried soil.
8. Bulk Density = $(\text{mass}_{\text{drysoil+container}} - \text{mass}_{\text{container}})/(\text{volume}_{\text{cylinder}})$ $[M/L^3]$
9. VWC = $((\text{mass}_{\text{wetsoil+container}} - \text{mass}_{\text{container}}) - (\text{mass}_{\text{drysoil+container}} - \text{mass}_{\text{container}}))/(\text{volume}_{\text{cylinder}})$ $[M/L^3]$
10. %O.M. = $(\text{mass}_{60°\text{C-container}} - \text{mass}_{110°\text{C-container}})/\text{mass}_{60°\text{C-container}}$

5.2 MPS-1

Figure 3. Good hydraulic contact with MPS-1.

Special care should be taken when handling the MPS-1 for several reasons. First, the ceramic chips of the MPS-1, which measure the water potential of the two ceramic disks, are somewhat brittle and can easily crack or chip. Although one or two small chips on the edge of the disk will not significantly affect sensor accuracy, a cracked ceramic will result in a loss of accuracy (Decagon Devices, Inc., 2008). Second, for the MPS-1 to accurately measure water potential, the ceramic disks must be able to readily take up water. If the ceramic is exposed to oils or other hydrophobic substances, then the ability of the disks to take up water from the soil can be compromised, leading to slow equilibration times and/or loss of accuracy (Decagon Devices, Inc., 2008). Therefore exposure of the ceramic material to skin oils or other hydrophobic compounds should be minimized.

6. Field Installation

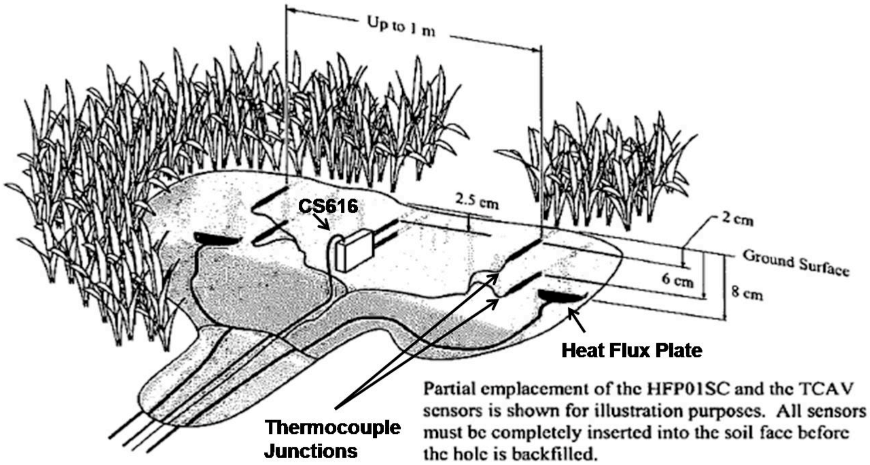
6.1 Soil excavation and probe insertion

Figure 4. Excavated installation pit.

1. Choose an area with soil characteristics representative of the study area. Use a shovel to dig a pit to the desired depth, leaving the higher-elevation wall of the soil pit undisturbed (Figure 4). Placing the sensor in the pit wall with the highest land surface elevation minimizes measuring unnatural soil moisture content that could be created due to surface and subsurface flow and preferential flow paths created during digging.
2. Try to keep the excavated soil in shape and sorted by depth, so the original soil horizons are maintained for the purpose of backfilling the pit somewhat close to natural conditions.
3. Install soil sensors in the side of the pit associated with the upgradient land surface so that draining soil water is not biased by disturbed soil (Figure 4). Sensors should also be installed in an undisturbed portion of the soil pit wall, so original bulk density is maintained. If the surface

of the wall is compacted while digging, use a hand trowel to scrape away the altered surface until undisturbed soil is reached.

4. Considerations when installing the ECH2O-TM include avoiding: (1) air gaps or extremely compact soil surrounding the probe and (2) installation within 5 cm of large metal objects, which can attenuate the probes' electromagnetic field and distort output readings. Also, avoid catching nonsoil material between the probe prongs, such as sticks, bark, roots, rocks or other material, which will adversely affect readings (Decagon Devices, Inc., 2007). Be careful when inserting the probes into dense soil, as the prongs will break if excessive force is used. A micro spatula, often used in laboratories, is an ideal width and thickness to use to make pilot slits into the pit wall in which to insert the ECH2O-TM.
5. Before installing the MPS-1, ensure that good hydraulic contact exists with the ceramic plate and surrounding soil (Figure 3). To obtain this contact, take some native soil from the layer of soil the MPS-1 will be installed in, wet it, and pack it in a ball around the entire MPS-1, making sure the moist soil is in contact will all ceramic surfaces. Make a hole in the pit wall just large enough for the MPS-1 and ball of soil. Press the MPS-1 and soil firmly into the hole and backfill the hole to natural conditions leaving no gaps around the soil encased sensor. With sandy soils, adherence when wet may not be possible, so pack the sensor into the soil at the bottom of the installation pit. This step will need to be repeated prior to installing each MPS-1 sensor.
6. Install the MPS-1 and ECH2O at a depth of 100 cm.
7. Mark the sensor installation depth on a piece of marking tape attached to each sensor and on the end of each sensor wire, so this information can be input to the datalogger program following completion of sensor deployment.



Partial emplacement of the HFP01SC and the TCAV sensors is shown for illustration purposes. All sensors must be completely inserted into the soil face before the hole is backfilled.

Figure 5. Sensor Placement within the undisturbed portion of the soil (Campbell Scientific).

8. Repeat steps 6 and 7 at a depth of 50 cm.
9. In addition to installing the ECH2O and MPS-1 sensors at 50 cm install one of the CS-616s and a thermocouple. Install these two sensors similar to the drawing in Figure 5, excluding the two heat flux plates.
10. Install an additional set of thermocouples at 20 cm.
11. At a depth of 8 cm beneath the ground surface make a slice in the soil profile large enough to slide the heat flux plates in snugly. This surface depth aids in reducing errors associated with vapor transport of heat (Campbell Scientific, 2007).

12. Insert the plate in the soil with the red label facing upward and the blue label facing downward. Try to disturb as little soil as possible because disturbance can result in inaccurate soil heat flux measurements. Subsequently, ensure that heat flux plates are in full contact with the soil, as air pockets will produce inaccurate measurements.
13. To install the thermocouples, place two of them above each heat flux plate at depths beneath the ground surface of 6 cm and 2 cm. The soil thermocouples can be placed up to 1 meter apart (Campbell Scientific, Inc., 1990).

    Note: This is a guideline for installation (Campbell Scientific, Inc., 1990) and apart from the relationship with the soil heat flux plates, does not require exact depths.
14. Insert the thermocouples by pressing them into the soil, but make sure to keep them horizontal, or perpendicular to the pit wall.
15. For installation of the water content reflectometers (CS616), ensure that the probes are not deployed within 9 inches of one another or measurements may be erratic (Campbell Scientific, Inc., 2006).
    a. If the soil has a high electrical conductivity which is common in compact, clayey soils, then the calibration must be adjusted for the medium (Campbell Scientific, Inc., 2006). Accuracy using the factory supplied standard calibration coefficient is ±2.5% if the soil has a bulk electrical conductivity less than 0.5 dS/m, bulk density less than 1.55 g/cm^3 and clay content less than 30% (Campbell Scientific, Inc., 2006).
16. When inserting the CS616 probes, keep the rods as close to parallel as a possible in order to maintain the probe's design wave guide geometry (Campbell Scientific, Inc., 2006). Try to reduce the air around the probe as air will result in decreased measurement accuracy and most likely indicate lower water content.
    a. If the soil is rocky or dense, create an insertion guide so the probes are not scratched upon insertion. An unfolded wire clothing hanger is one example of a tool that can be used for this purpose.
17. To detect the passing of a wetting front, insert the probes horizontally.
18. To minimize thermal conduction, bury the sensor leads so they run back from the pit a short distance through the ground to the surface. Do not run the wires directly to the surface (Campbell Scientific, Inc., 2007).
    a. After installing the sensors, ensure they work properly by checking their output from the datalogger (Figure 6). Next, backfill the excavated hole to bury the sensors with care taken to re-pack the soil layers in the order they were removed and to maintain the soil's original bulk density. Minimizing soil disturbance during excavation helps to maintain the soil's original bulk density.

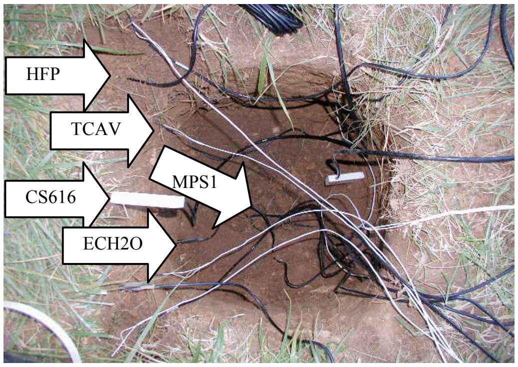


Figure 6. Final installation of CUERE's soil sensors.

    b. Leave at least six inches of sensor cable beneath the soil before bringing the cable to the surface. The cable should never be bent in a tight radius as it leaves the sensor body. At least four inches of cable should exit the sensor body in a straight line before bending the cable (Campbell Scientific, Inc., 2007).

19. The datalogger should be placed in a weatherproof instrument enclosure and the power cables and battery (if used) should also be housed within this box. The datalogger should be electrically grounded by connecting a 10 AWG stranded copper wire between the CR1000 grounding lug and a ½-inch copper grounding rod inserted into the ground.
20. Use putty around the holes of the box to make sure that insects and small rodents cannot enter the box.
21. The extra length of cables should be coiled and stored off of the ground so that the cables are less likely to be gnawed on by rodents (Figure 7).

Figure 7. Coiled sensor cables stored off the ground.

6.2 Power

A constant voltage power supply should be used to power the datalogger and sensors. Voltage from a battery has less variation than AC power which can fluctuate as power consumption fluctuates on the circuit. A battery source is recommended because many sensors detect environmental conditions using changes in voltage and their accuracy is dependent on consistent input voltage.

In order to maintain a non-fluctuating power source, the battery must be constantly charged. If AC power is being used to supply constant power to the battery charger, the female end of a power extension cord should be cut off so it can fit through the opening of the enclosure and the exposed wires of the extension cord fed through the opening in the instrument enclosure. Once the exposed wires of the extension cord have been fed through the opening, the purchased outlet receptacle should be connected to the exposed wires so the battery charger can be plugged in. Prior to cutting the extension cord, be sure to unplug any external power source. Use the AC power source to power a float battery charger (Powersonic, Float Battery Charger PSC 12800 A-C) and attach the float charger to the battery. A float charger safely maintains a battery at full charge without overcharging it.

6.3 Removal

Prior to removing the sensors, the soil pit will need to be excavated. Care should be taken when excavating the soil pit so that cables are not severed and/or otherwise compromised. When removing the ECH2O, CS616 and MPS-1 probes, be careful not to pull on the cables as this can break the internal wires and cause the probes to malfunction. When removing the soil thermocouples grip the tubing and not the thermocouple wiring.

6.4 Maintenance

Maintenance of all sensor cables requires that wires/cables be checked periodically for rodent damage. In addition, the heat flux plates must be re-calibrated every two years (Campbell Scientific, Inc., 2007).

7. Considerations for a Soil Sensor Network

7.1 Sensor updates

Decagon is currently developing the ECH2O-TM with SDI-12 communication protocol that will interface with up to 10 probes using one CR1000 control port. If ECH2O-TM sensors use SDI-12 protocol, a less expensive datalogger such as the Campbell Scientific CR200 or CR10X could be used to control all of the soil sensors.

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Appendix A: Sample Wiring Description

*** Wiring ***

ANALOG INPUT

1H	CS616 #1 signal (green) 'CS616 50 cm depth
1L	CS616 #2 signal (green) 'CS616 2.5 cm depth
2H	HFP01 #1 signal (white) 'HFP01 closest to Hazmat
2L	HFP01 #1 signal reference (green)
gnd	HFP01 #1 shield (clear)
3H	HFP01 #2 signal (white) 'HFP01 closest to Tech 2
3L	HFP01 #2 signal reference (green)
gnd	HFP01 #2 shield (clear)
4H	TCAV #1 signal (purple) 'TCAV at 50 cm depth
4L	TCAV #1 signal reference (red)
gnd	TCAV #1 shield (clear)
5H	TCAV #2 signal (purple) 'TCAV at 20 cm depth
5L	TCAV #2 signal reference (red)
gnd	TCAV #2 shield (clear)
6H	TCAV #3 signal (purple) 'TCAV at 2 and 5 cm depth
6L	TCAV #3 signal reference (red)
gnd	TCAV #3 shield (clear)
VX2	MPS #1 signal (white) 'MPS at 10 cm depth
SE 14	MPS #1 signal reference (red)
gnd	MPS #1 shield (silver)
VX1	MPS #2 signal (white) 'MPS at 50 cm depth
SE 15	MPS #2 signal reference (red)
gnd	MPS #2 shield (silver)
VX3	MPS #3 signal (white) 'MPS at 100 cm depth
SE 16	MPS #3 signal reference (red)
gnd	MPS #3 shield (silver)

CONTROL PORT

C1	CS616 #1 power control (orange)
C1	CS616 #2 power control (orange)
G	CS616 #1 shield (clear)
G	CS616 #2 shield (clear)

SW12V ALL WHITE (EXCITATION) WIRES

C4	TM #1 OUTPUT (RED) WIRE	'TM at 10 cm depth
C6	TM #2 OUTPUT (RED) WIRE	'TM at 50 cm depth
C8	TM #3 OUTPUT (RED) WIRE	'TM at 100 cm depth
GND	ALL BARE (GND) WIRES	

POWER OUT

'	CS616 #1 power (red)
'	CS616 #2 power (red)
'	CS616 #1 signal reference (black)
'	CS616 #2 signal reference (black)

POWER IN

12V	datalogger (red)
G	datalogger (black)