CAMPBELL SCIENTIFIC
TDR SOIL MOISTURE MEASUREMENT
SYSTEM MANUAL

REVISION: 2/92

TDR

WARRANTY AND ASSISTANCE

The following warranty applies to the **SDM1502 COMMUNICATION INTERFACE, PS1502B POWER CONTROL MODULE,** and the **SDMX50 50 OHM COAX MULTIPLEXER.**

These products 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.

Products may not be returned without prior authorization. To obtain a Returned Materials Authorization (RMA), contact CAMPBELL SCIENTIFIC, INC., phone (435) 753-2342. After an applications engineer determines the nature of the problem, an RMA number will be issued. Please write this number clearly on the outside of the shipping container. CAMPBELL SCIENTIFIC's shipping address is:

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

CAMPBELL SCIENTIFIC, INC. does not accept collect calls.

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

CAMPBELL SCIENTIFIC, INC.

815 W. 1800 N.	Campbell Scientific Canada Corp.	Campbell Scientific Ltd.
Logan, UT 84321-1784	11564 -149th Street	14-20 Field Street
USA	Edmonton, Alberta T5M 1W7	Shepshed, Leics. LE12 9AL
Phone (435) 753-2342	CANADA	ENGLAND
FAX (435) 750-9540	Phone (403) 454-2505	Phone (44)-50960-1141
www.campbellsci.com	FAX (403) 454-2655	FAX (44)-50960-1091

TDR SOIL MOISTURE MEASUREMENTS
TABLE OF CONTENTS

TDR SOIL MOISTURE MEASUREMENTS

Since the application and advantages of using Time Domain Reflectometry to measure soil water content were described by Topp, Davis, and Annan in 1980, the method has proven itself through the work of numerous researchers. Campbell Scientific has developed a system in which the Tektronix 1502B cable tester is coupled with a CR10 or 21X datalogger and multiplexers to provide automated multiple probe TDR soil moisture measurements.

1. INTRODUCTION

1.1 SOIL MOISTURE MEASUREMENT BY TIME DOMAIN REFLECTOMETRY

A waveform traveling down a coax or waveguide is influenced by the type of material surrounding the conductors. If the dielectric constant of the material is high, the signal propagates slower. Because the dielectric constant of water is much higher than most other materials, a signal within a wet or moist medium propagates slower than in the same medium when dry. Ionic conductivity affects the amplitude of the signal but not the propagation time. Thus, moisture content can be determined by measuring the propagation time over a fixed length probe embedded in the medium being measured.

This process of sending pulses and observing the reflected waveform is called Time Domain Reflectometry (TDR). TDR is also used to determine the location of failures in telecommunications cables and, on cables grouted in boreholes, to monitor rock mass deformation.

The reflectometer used in our system is the Tektronix 1502B TDR Cable Tester equipped with Campbell Scientific's SDM1502 Communications Interface and PS1502B Power Control Module. The Tektronix 1502C will also work but cannot use the PS1502B for controlling power.

1.2 PROBES AND CABLES

The simplest soil probe consists of two parallel rods inserted into the soil. These are attached directly to twin lead cable. The two rod probe and the twin lead cable that attaches to it carry a "balanced" signal (the signal travels on both leads).

The 1502B has a 50 ohm coax connector; coax carries an unbalanced signal. To convert from an unbalanced to a balanced signal, and to match impedances, a balancing transformer (balun) is needed. The PB30B (-RG8 or -RG58) is a two rod probe with 30 cm stainless steel rods; a balun molded into the cable joins the twin lead cable from the probe to the 1502B (or multiplexer).

Another type of probe that has come into use recently is the unbalanced probe. The probe has three or more rods. A central rod is connected to the signal lead of the coax. The other rods are arranged radially around the center and are connected to the shield of the coax. The volume of soil sampled with this configuration is smaller than with a balanced design and is concentrated around the center electrode. The probes connect directly to the 50 ohm coax cables used throughout the system. In dry soils, the unbalanced probe may produce a wave form that cannot be interpreted by the algorithm used to determine propogation velocity for the probe.

1.3 MULTIPLEXING

The SDMX50 is an eight to one 50 ohm coax multiplexer with BNC connectors. The coax cable coming from the 1502B connects to the common.

The eight multiplexed connections are used to connect additional multiplexers or probes. The PB30B connects directly to the SDMX50. Up to three levels of multiplexers may be used. Up to 512 soil probes may be measured on a fully expanded system.
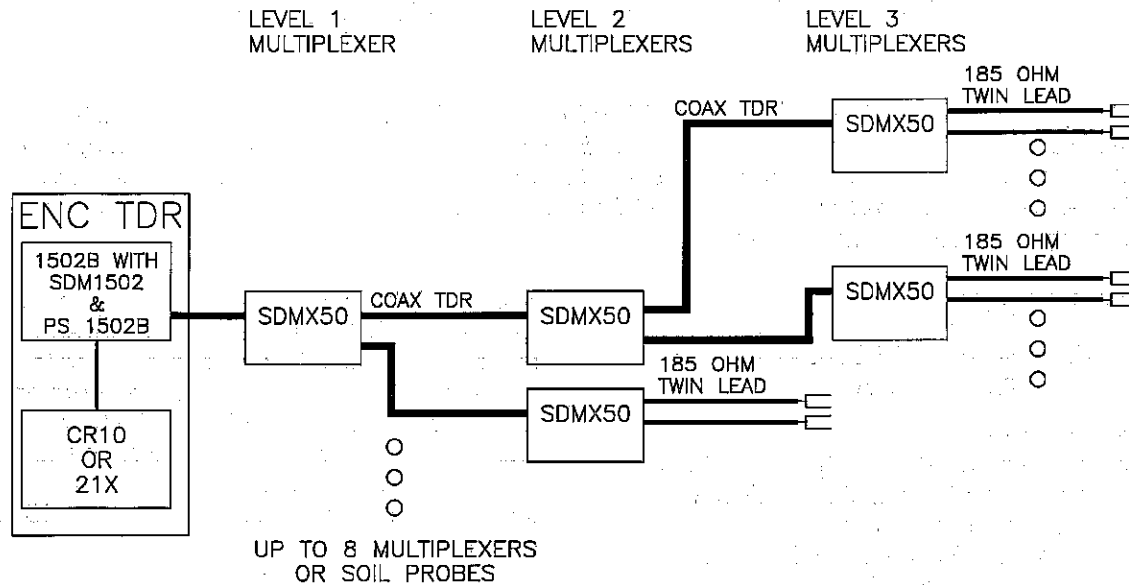
FIGURE 2-1. TDR System Components

2. SYSTEM COMPONENTS

1502B - Tektronix 1502B TDR Cable Tester.

SDM1502 - Communication Interface; this module plugs into the 1502B or 1502C and provides a Synchronous Device for Measurement (SDM) interface to a CR10 or 21X datalogger.

PS1502B Power Control Module plugs into the battery receptacle of the 1502B; provides for connection to an external 12 VDC source and allows the datalogger to control power to the 1502B.

SDMX50 - 50 Ohm Coax Multiplexer - 8 to 1, BNC connectors, enclosure included. This multiplexer is used to connect additional multiplexers or probes. Balanced probes attached to this multiplexer require a balun for each probe.

PB30B (-RG8 or -RG58) - 30 cm soil probes; two rods, balanced design, with balun molded in cable. A BNC connector on the coax cable attaches directly to SDMX50. The -RG8 version uses a low loss coax cable. The -RG58 version uses RG58 coax cable.

COAX TDR - 50 ohm coax cable with BNC connectors for connecting multiplexer.

6549 - 5 conductor cable used for SDM connection between datalogger and multiplexers.

21X or CR10 - The datalogger communicates with the 1502B and multiplexers with the SDM interface using control ports 1-3 (and single ended channel 1 on the 21X). An additional control port is used to switch power to the 1502B.

ENC TDR - Enclosure to hold 1502B and datalogger. The ENC TDR includes a transient suppressor and cabling for connecting the power supply and datalogger. The 1502B mount allows it to swing out to view screen.

Datalogger Software - Special PROMS for the CR10 or 21X datalogger include Instruction 100 for controlling the 1502B and multiplexers.

6590 - Transient suppressor attaches to cable from 1502B and is required if ENC TDR is *not* purchased.

3. INSTALLATION

The 1502B and datalogger are housed in the ENC TDR. In most instances power is supplied from an external 12 volt deep cycle battery charged by a MSX18R solar panel. Each SDMX50 multiplexer has its own enclosure.

Coax cable connects the 1502B and the SDMX50 and SDMX50 to other SDMX50s. In addition to the coax cable that carries the TDR signal, the multiplexers must be connected to the datalogger by a 5 conductor cable which provides power to the multiplexers and allows the datalogger to control the multiplexer switching.

3.1 ASSIGNING ADDRESSES

The SDM1502 and SDMX50 are Synchronous Devices for Measurement (**SDM**); the datalogger communicates with these devices via control ports 1, 2, and 3 (and analog channel 1H on the 21X). Addresses set in the devices allow the datalogger to communicate with the correct device.

There are sixteen possible addresses; a maximum of four are used in a TDR system. The address assigned the SDM1502 determines the addresses that need to be assigned to the multiplexers: The multiplexer with its input connected to the cable from the 1502B is level 1, level 2 multiplexers are those connected to the level 1 multiplexer, level 3 multiplexers are those connected to a level 2 multiplexer. No more than 3 levels of multiplexers are allowed. The level 1 address is 1 greater than that of the SDM1502. All level 2 multiplexers have the address set to that of the SDM1502 plus 2 and all level 3 multiplexers have the address set to that of the SDM1502 plus 3. The addresses are in base 4 (Table 3-1); for example, if the SDM1502 address is 22, the addresses for level one, level two, and level three multiplexers are 23, 30 and 31, respectively.

The address for the SDM1502 is set with switches; the switches can be reached through an access hole in the case (Figure 3-1). Table 3-1 lists the address settings.
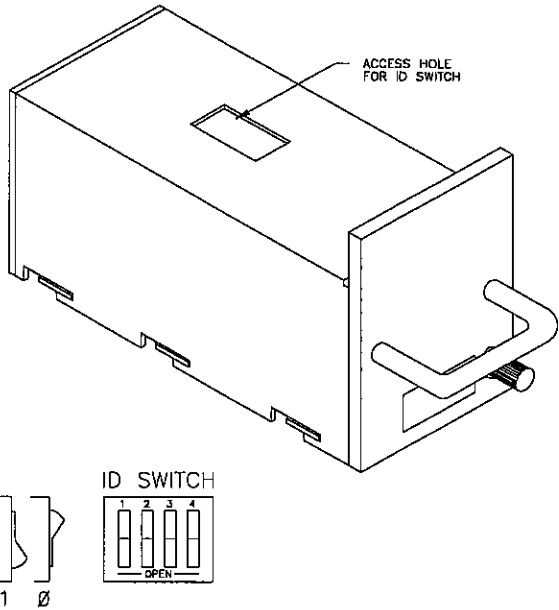
FIGURE 3-1. Address Switch on SDM1502

The address for the SDMX50 is set with jumpers. There are two jumpers on each multiplexer. The jumpers are labeled MSD for Most Significant Digit and LSD for Least Significant Digit. Each jumper has four pairs of pins. Depending which pair of pins is connected with the jumper, the digit can have the value of 0, 1, 2, or 3 (Figure 3-2). Table 3-1 lists the address settings.

FIGURE 3-2. Location of Address Jumpers on SDMX50

FIGURE 3-3. Mounting 1502B in ENC TDR

TABLE 3-1. SDM Addresses

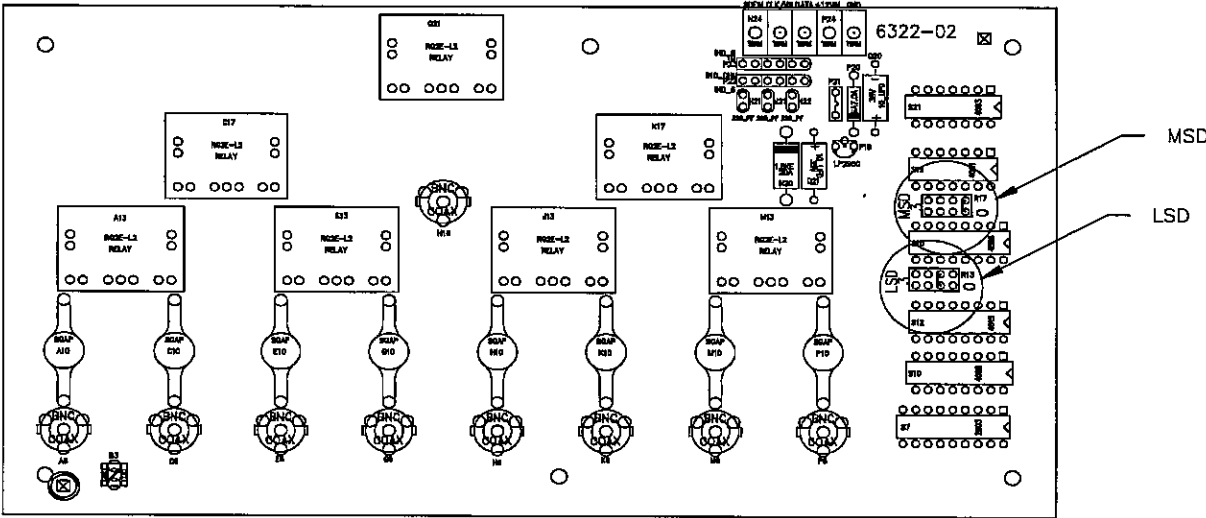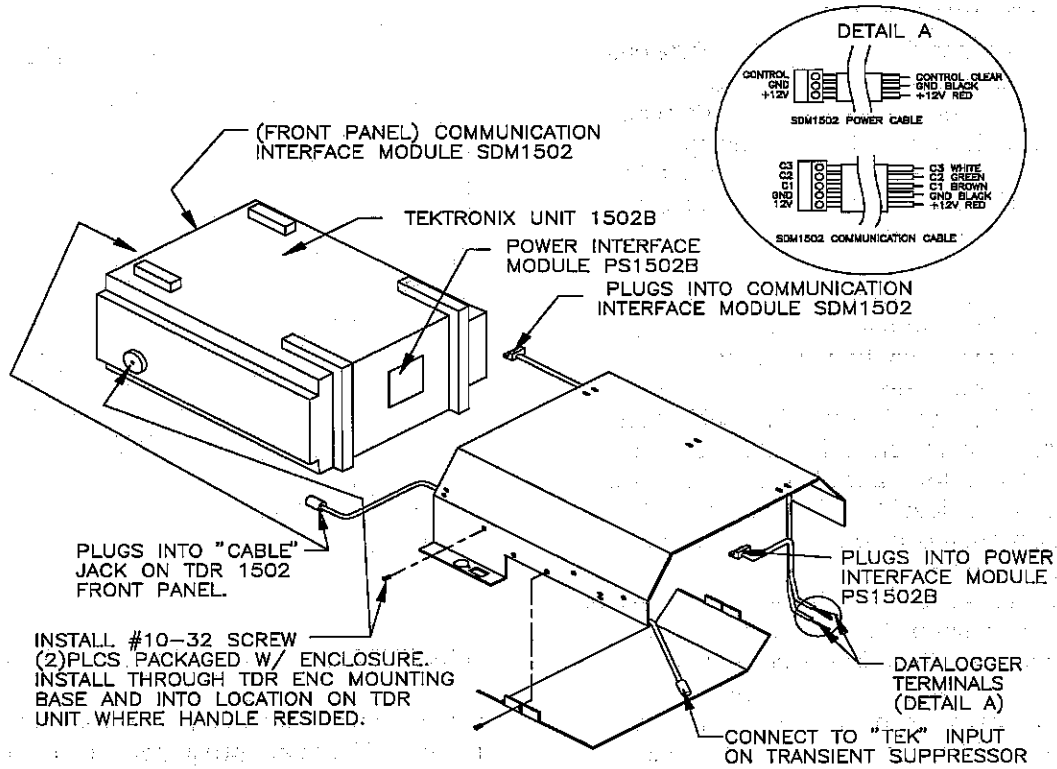| ADDRESS Base 4	SDM1502 Switches 1 2 3 4	SDMX50 Jumper Settings MSD	SDMX50 Jumper Settings LSD
00	0 0 0 0	0	0
01	1 0 0 0	0	1
02	0 1 0 0	0	2
03	1 1 0 0	0	3
10	0 0 1 0	1	0
11	1 0 1 0	1	1
12	0 1 1 0	1	2
13	1 1 1 0	1	3
20	0 0 0 1	2	0
21	1 0 0 1	2	1
22	0 1 0 1	2	2
23	1 1 0 1	2	3
30	0 0 1 1	3	0
31	1 0 1 1	3	1
32	0 1 1 1	3	2
33	1 1 1 1	3	3

3.2 INSTALLING 1502B IN ENC TDR

The 1502B is mounted in the ENC TDR enclosure by removing the handle (the required Allen wrench is included with the ENC TDR) and installing as shown in Figure 3-3.

3.3 DATALOGGER WIRING

3.3.1 SDM Wiring

Figure 3-4 shows the wiring of the SDM communication cables from the SDM1502 and SDMX50 to the datalogger. With the 21X, the C1 connection from the SDM1502 must be wired into analog input 1H with a 10 kilohm resistor to C1. (This resistor is the short black cable that is fastened to the SDM1502 handle with a wire tie for shipping.) The resistor is not used with the CR10.

> The SDM1502 terminals are labeled above the connector. The description for the multiplexer terminals is on a label inside the enclosure lid.
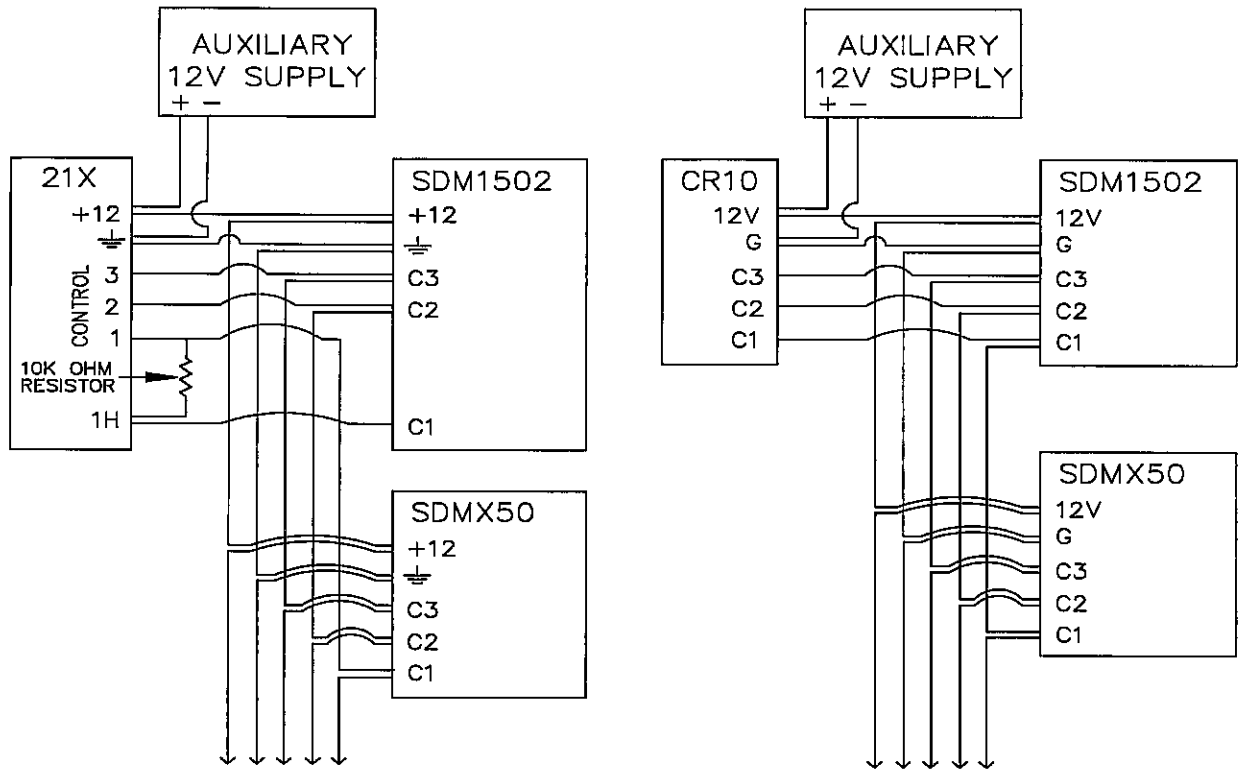
FIGURE 3-4. SDM Wiring

3.3.2 PS1502B

The PS1502B has three connections to the datalogger: +12, Ground, and a control input which allows the datalogger to switch the power to the 1502B. In the example program (Section 5), the control input is connected to control port 4.

3.4. SOIL PROBES

The PB30 consists of two 30 centimeter stainless rods and a twinlead cable. The probes are shipped without the cable attached. The rods are attached with the supplied screw and star washer (Figure 3-5).

The two rods of the probe are pressed into the soil with the rods parallel. The cable leads allow the common 5 centimeter rod spacing.

The cable on the probe has a BNC connector that connects directly to the SDMX50.

FIGURE 3-5. PB30 Assembly

5

3.5 GROUNDING

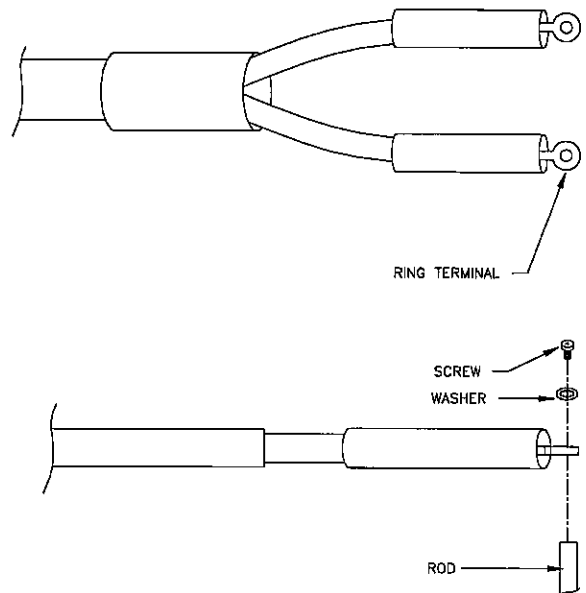The TDR system should be installed with a single ground point. A good earth ground should be established close to the datalogger/1502B.

A copper clad grounding rod comes with the CM10 tripod or may be obtained along with necessary clamps and wire from an electrical supply house.

The ENC TDR has ground connections for the datalogger, 1502B and 6590 Transient Suppressor which are connected to a grounding lug in the lower left corner of the enclosure. A short run of heavy gage (10 AWG or lower) wire should be connected from the lug to the earth ground.

The ground lug on the multiplexer enclosures should only be used if the multiplexer is close enough to conveniently use the same ground point as the datalogger.

3.6 BATTERY CONNECTIONS

Two terminal strip adapters for the battery posts are provided with the ENC TDR (Figure 3-6). These terminal strips will mount to the wing nut battery posts on most deep cycle lead acid batteries.
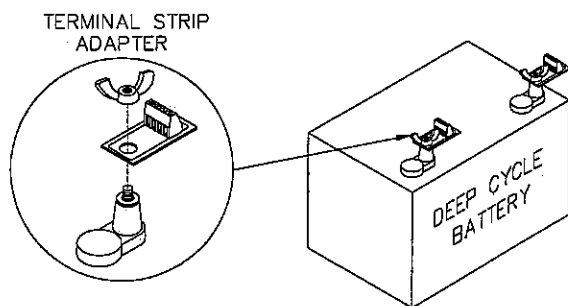

FIGURE 3-6. Terminal Strip Adapters for Connections to Battery

4. PROGRAMMING INSTRUCTION 100

Instruction 100 is used to make TDR measurements. A separate Instruction 100 is entered for each multiplexer that has probes to be measured or to measure separate groups of probes on a single multiplexer.

Options in instruction allow:

finding a soil moisture probe automatically or specifying the "distance" to the probe

calculating water content or storing raw waveform data

the starting point and time resolution of the raw waveform.

Instruction 100 may also be used to step through the multiplexers while manually controlling the 1502B to examine the waveforms, and to check the signature of the PROM in the SDM1502

INSTRUCTION 100 PARAMETERS

PAR. NO.	DATA TYPE	DESCRIPTION
01:	2	SDM1502 address
02:	2	Output option
		0 Water content
		1 Raw data
		98 Manual step through
		99 SDM1502 signature
03:	FP	Probe length, meters
04:	FP	Cable length, meters; enter 0 for auto search
05:	4	Multiplexer channel/Reps
		A B C D
		A Chan. of 1st Mux, 0 if none
		B Chan. of 2nd Mux, 0 if none
		C Chan. of 3rd Mux, 0 if none
		D No. of Probes to scan
06:	4	Input location
07:	FP	Multiplier
08:	FP	Offset

Input Locations altered:
    Water content - 1 per probe scanned
      Raw data - 256 per probe scanned

Intermediate Locations required:
    531 the first time Instruction 100 is used
    16 intermediate locations for each
        Instruction 100 thereafter.

Parameter 1, address: the address set into the SDM1502 (Section 3.1).

Parameter 2 output option:

"Water Content", Code 0: the instruction determines the end points of the probe using the algorithm described by Baker and Allmaras,

1990, and calculates $1/V_p$; the multiplier and offset (parameters 7 and 8) may be used to obtain the result directly in volumetric water content (Section 5).

"Raw data", Code 1: 256 values are output for each probe measured; the 251 values from the waveform followed by the distance to the cursor in meters, the distance between waveform points, the gain, the offset, and the sample number.

"Manual Step Through", Code 98: When the program is compiled and run, the 1502B will be left under manual control and the datalogger will switch to the first channel and pause. To switch to the next channel, set flag 8 (*6 Mode or with TERM); the datalogger will switch to the next channel and set flag 8 low. Repeatedly setting flag 8 allows the user to step through all programmed channels.

"Signature", Code 99: The signature of the PROM in the SDM1502 is calculated and stored in the location specified in parameter 6.

Parameter 3, Probe Length: The length of the soil probe in meters. This length is used to calculate the water content result (apparent length divided by actual length, or $1/V_p$), and to determine the time/length resolution of the waveform captured for the water content calculation or raw output.

The probe length parameter is used to set the resolution of the raw waveform for applications where there is no actual "probe length". Table 4-1 lists the distance per division used at different probe lengths.

TABLE 4-1. Waveform Resolution Determined by Probe Length

Probe Length			Distance/Division
0	to	0.02	0.025
0.03	to	0.06	0.05
0.07	to	0.13	0.1
0.14	to	0.2	0.25
0.3	to	0.4	0.5
0.5	to	0.9	1.0
1.0	to	2.0	2.5
2.1	to	4.3	5.0
4.4	to	9.2	10.0
9.3	to	9.9	25.0
	>	10.0	50.0

Parameter 4 Cable length: The "length" in meters to the probe or 1502B cursor. Enter "0" and the datalogger will automatically search for the soil probe.

This "length" is not the actual length as measured with a meter stick; it is the distance the 1502B measures using a propagating velocity of 0.99 the speed of light ($V_p = 0.99$).

When capturing the waveform for raw output or calculating water content, the cursor (start of probe) is placed 1 division into the 1502B display (10 divisions total).

If an automatic search for the soil probe fails, and it is desired to enter the length to the cable, it can be determined by manually stepping through the multiplexer and finding the probe with the 1502B display.

Parameter 5, Multiplexer channel/Reps: Determines the multiplexer, first measurement channel, and number of probes to measure. The entry required is: channel number on level 1 multiplexer, channel on level 2 multiplexer, channel on level 3 multiplexer, and number of probes to measure. For example, 1008 would indicate that there is 1 multiplexer; start on channel 1 and step through 8 probes. The entry 2318 tells the datalogger to set the level one multiplexer to channel 2, the level two multiplexers to channel 3, and measure 8 probes that are connected to channels 1-8 on the level 3 multiplexer.

Parameter 6, Input location: The Input location in which to start storing data. When outputting water content, one location is used for each probe measured. When outputting raw data, 256 locations are required for each repetition.

5. CALIBRATION FOR WATER CONTENT

When the water content output option is selected, the datalogger calculates the ratio of the apparent length of the probe (the 1502B results are in terms of length) to the actual length as entered in parameter 3. The datalogger corrects the length to what it would be if the propagation velocity was the speed of light. Thus, the ratio of lengths is the same as the ratio of the speed of light divided by the velocity of the signal down the probe.

The propagating velocity, V_p is defined as the ratio of the actual velocity divided by the speed of light. The result from the datalogger (with a multiplier of 1 and an offset of 0) is $1/V_p$.

A multiplier of 0.1138 and an offset of -0.1758 gives volumetric water fraction using the calibration of Ledieu et. al. 1986 (normalized to accommodate probes of varying length):

$$W_v = 0.1138/V_p - 0.1758$$

Topp et. al. 1980, used a third order equation to equate volumetric water content, W_v, to apparent dielectric constant Ka. $Ka=(1/V_p)^2$; with this substitution, the equation is

$$W_v= -0.053+0.0292(1/V_p)^2-0.00055(1/V_p)^4$$

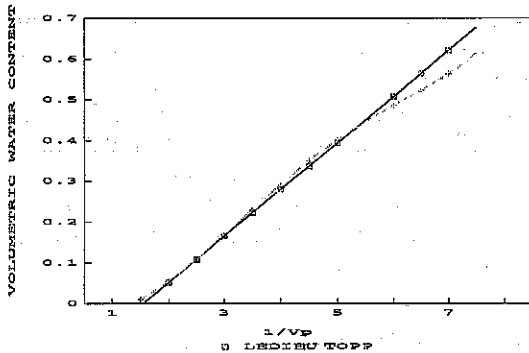$$+0.0000043(1/V_p)^6$$

Example 2 uses Topp's calibration.

FIGURE 5-1. Comparison of Calibrations from Topp and Ledieu

6. PROGRAMMING EXAMPLES

There are several things to keep in mind when writing a datalogger program to make TDR measurements:

1. Set the control port high that controls the PS 1502B 5 seconds prior to executing Instruction 100. Switch it off after all measurements are made.

2. TDR measurements require considerably more time than other measurements (approximately 1 minute each on the first pass when finding the probe and 15 to 20

seconds each on subsequent measurements). The program must be written so that analog measurements, output intervals other time based decisions take this into account.

Switching power to the 1502B is valuable not only for the conservation of batteries; it also allows the 1502B to be reset if it should "bomb". If the 1502B or 1502C does not respond correctly to the datalogger's commands, -99999 will be loaded into the input locations that would normally contain the results of the measurements.

6.1 EXAMPLE 1, MEASURE AND RECORD EVERY HOUR

The following program is executed once an hour. A single multiplexer with eight probes is measured. The 1502B is switched on, the measurements made with output in water content using Ledieu's calibration, the 1502B is switched off, and the time and 8 water content measurements are output to Final Storage.

*	1	Table 1 Programs
01:	3600	Sec. Execution Interval
01:	P86	Do
01:	44	Set high Port 4
02:	P22	Excitation with Delay
01:	1	EX Chan
02:	0	Delay w/EX (units=.01sec)
03:	500	Delay after EX (units=.01sec)
04:	0	mV Excitation
03:	P100	SDM-1502
01:	11	Address
02:	0	Moisture
03:	.3	Probe length (meters)
04:	0	Cable length (meters)
05:	1008	MMMP--Mux channels & Probes
06:	1	Loc [:WATER #1]
07:	0.1138	Mult
08:	-0.1758	Offset
04:	P86	Do
01:	54	Set low Port 4
05:	P86	Do
01:	10	Set high Flag 0 (output)
06:	P77	Real Time
01:	110	Day,Hour-Minute

07:	P70	Sample
01:	8	Reps
02:	1	Loc WATER #1
08:	P	End Table 1
*	A	Mode 10 Memory Allocation
01:	28	Input Locations
02:	540	Intermediate Locations

6.2 EXAMPLE 2, HOURLY AVERAGE USING TOPP'S CALIBRATION

In this example measurements are made every 15 minutes and the average is output each hour.

Note that Instruction 92, that sets the output flag, is placed ahead of Instruction 100. Instruction 92 has to be executed within the specified minute in order to execute the command. If it were after Instruction 100, the actual time of execution would be a minute or more after the even 15 minute interval on which the table is executed (i.e., Flag 0 would never be set).

This program uses Topp's calibration. A multiplier of 1 and an offset of 0 results in output of $1/V_p$ from Instruction 100. This result is squared and multiplied by 0.1 before being operated on by the polynomial. The factor of 0.1 allows the coefficients for the polynomial to be scaled so all significant digits can be entered in the polynomial Instruction 55.

*	1	Table 1 Programs
01:	900	Sec. Execution Interval
		Every 15 minutes
01:	P92	If time is
01:	0	minutes into a
02:	60	minute interval
03:	10	Set high Flag 0 (output)
02:	P77	Real Time
01:	110	Day,Hour-Minute
03:	P86	Do
01:	44	Set high Port 4
04:	P22	Excitation with Delay
01:	1	EX Chan
02:	0	Delay w/EX (units=.01sec)
03:	500	Delay after EX (units=.01sec)
04:	0	mV Excitation

05:	P100	SDM-1502
01:	11	Address
02:	0	Moisture
03:	.3	Probe length (meters)
04:	0	Cable length (meters)
05:	1008	MMMP--Mux channels & Probes
06:	1	Loc [:Wv #1]
07:	1	Mult
08:	0	Offset
06:	P86	Do
01:	54	Set low Port 4
07:	P87	Beginning of Loop
01:	0	Delay
02:	8	Loop Count
08:	P36	Z=X*Y
01:	1--	X Loc Wv #1
02:	1--	Y Loc Wv #1
03:	1--	Z Loc [:Wv #1]
09:	P37	Z=X*F
01:	1--	X Loc Wv #1
02:	.1	F
03:	1--	Z Loc [:Wv #1]
10:	P95	End
11:	P55	Polynomial
01:	8	Reps
02:	1	X Loc Wv #1
03:	1	F(X) Loc [:Wv #1]
04:	-0.053	C0
05:	.292	C1
06:	-0.055	C2
07:	0.0043	C3
08:	0	C4
09:	0	C5
12:	P71	Average
01:	8	Reps
02:	1	Loc Wv #1
13:	P	End Table 1
*	A	Mode 10 Memory Allocation
01:	28	Input Locations
02:	550	Intermediate Locations

6.3 EXAMPLE 3, TDR MEASUREMENTS IN TABLE 2 WITH ANALOG MEASUREMENTS IN TABLE 1

This example is for 4 multiplexers. The level 1 multiplexer has a multiplexer connected to each of channels 1, 2, and 3 and probes connected to channels 4 through 8. The second level multiplexers each have 8 probes. The measurements are made every 30 minutes and the averages are output every 4 hours.

Placing the TDR measurements in Table 2 allows analog measurements to be made in Table 1. The analog measurements will continue to be made during TDR measurements because Table 1 can interrupt Table 2.

The interruption cannot take place if the output flag is set in Table 2. Note that Instruction 92 is used to set flag 1 every 4 hours prior to making the TDR measurements. After making the measurements, flag 1 is checked to see if it is time for output.

```
*        1          Table 1 Programs
 01:     10         Sec. Execution Interval
```

Table 1 contains the program for making analog measurements; for example, a meteorological station or a number of soil temperatures. The measurements in Table 1 will be made at their scheduled interval even while the TDR measurements are made in Table 2 because Table 1 can interrupt Table 2.

```
 01:     P          End Table 1

*        2          Table 2 Programs
 01:     60         Sec. Execution Interval

 01:     P92        If time is
 01:     0          minutes into a
 02:     30         minute interval
 03:     30         Then Do

 02:     P92        If time is
 01:     0          minutes into a
 02:     240        minute interval
 03:     11         Set high Flag 1

 03:     P86        Do
 01:     44         Set high Port 4
```

```
 04:     P100       SDM-1502
 01:     22         Address
 02:     0          Moisture
 03:     .3         Probe length (meters)
 04:     0          Cable length (meters)
 05:     4005       MMMP--Mux channels & Probes
 06:     21         Loc [:MUX 1 #1 ]
 07:     0.1138     Mult
 08:     -.1758     Offset

 05:     P100       SDM-1502
 01:     22         Address
 02:     0          Moisture
 03:     .3         Probe length (meters)
 04:     0          Cable length (meters)
 05:     1108       MMMP--Mux channels & Probes
 06:     26         Loc [:MUX 2-1#1]
 07:     0.1138     Mult
 08:     0.1758     Offset

 06:     P100       SDM-1502
 01:     22         Address
 02:     0          Moisture
 03:     .3         Probe length (meters)
 04:     0          Cable length (meters)
 05:     2108       MMMP--Mux channels & Probes
 06:     34         Loc [:MUX 2-2#1]
 07:     0.1138     Mult
 08:     0.1758     Offset

 07:     P100       SDM-1502
 01:     22         Address
 02:     0          Moisture
 03:     .3         Probe length (meters)
 04:     0          Cable length (meters)
 05:     3108       MMMP--Mux channels & Probes
 06:     42         Loc [:MUX 2-3#1]
 07:     0.1138     Mult
 08:     0.1758     Offset

 08:     P86        Do
 01:     54         Set low Port 4

 09:     P91        If Flag/Port
 01:     11         Do if Flag 1 is high
 02:     10         Set high Flag 0 (output)

 10:     P86        Do
 01:     21         Set low Flag 1

 11:     P77        Real Time
 01:     110        Day,Hour-Minute

 12:     P71        Average
 01:     29         Reps
 02:     21         Loc MUX 1 #1
```

13:	P95	End
14:	P	End Table 2

*	A	Mode 10 Memory Allocation
01:	50	Input Locations
02:	700	Intermediate Locations

LITERATURE CITED

Baker, J.M. and R.R. Allmaras. 1990. System for Automating and Multiplexing Soil Moisture Measurement by Time-Domain Reflectometry. *Soil Science Society of America Journal* 54: 1-6.

Ledieu, J., P. DeRidder, P. DeClerck and S. Dautrebande. 1986. A Method of Measuring Soil Moisture by Time-Domain Reflectometry. *Journal of Hydrology* 88: 319-328.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic Determination of Soil Water Content: Measurements in Coaxial Transmission Lines. *Water Resources Research* 16.3: 574-582.