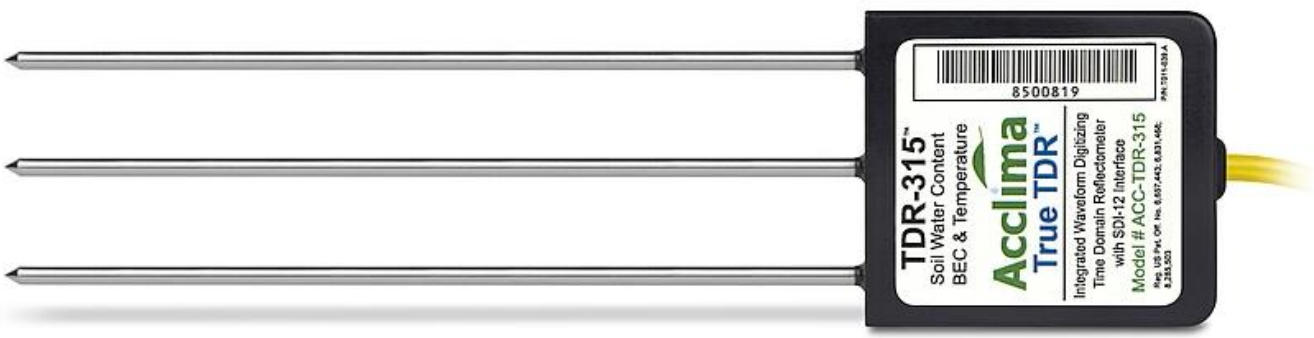
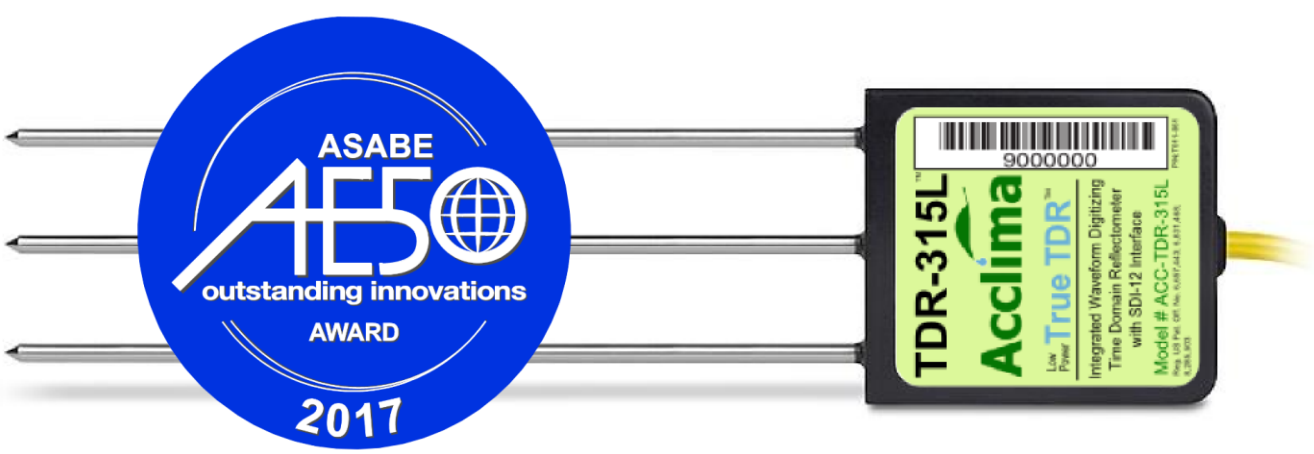
User Manual:
True TDR-315 & TDR-315L

Volumetric Water Content | Temperature | Permittivity | Bulk Electrical Conductivity | Soil Pore Water EC

Part Number: ACC-TDR-315 and ACC-TDR-315L





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Notices:

The Acclima True TDR-315 uses the industry standard SDI-12 interface for communicating with a Data Recorder or other SDI-12 equipped controller device. The SDI-12 communications standard is digital serial data communications hardware and protocol standard based on 1200 baud, ASCII character communications over the three-wire BUS. The SDI-12 Series is compliant with Version 1.3 of the SDI-12 standard. Version 1.3 is the latest standard at the time of this printing November, 2016.

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Firmware and Manual Disclaimer:

This manual was prepared for the current sensor firmware release at the time of the manual publication. The manual has been thoroughly edited and is believed to be reliable. Acclima assumes no liability for inaccuracies.

Errata may be published on our website or when deemed necessary by Acclima. Acclima reserves the right to change any specification(s) without notice.

You can learn more about Acclima's products at www.acclima.com or by emailing your questions to sales@acclima.com.

Product Introduction:

The Acclima TDR-315 series sensor is a genuine Time Domain Reflectometer – complete with an integrated 150ps rise-time step function generator (350ps for the TDR-315L), a 15 cm waveguide, a 5ps resolution waveform digitizer and a precision time base that measures waveform temporal features as short as 5ps and as long as 20ns. The built-in algorithms in its floating point micro-processor search the digitized waveform and capture the incident and reflected wave time ordinates and from these the permittivity of the medium surrounding the waveguide is calculated using the first-principals-based EM propagation equation. From that a proprietary dielectric mixing model calculates the water content of the medium. The mixing model matches the Topp Equation very closely up to around 46% water content but behaves in a more representative fashion up to 100% water content – providing the assurance that the TDR-315 can be used in all applications including slurries where water content may reach 100%.

A precision thermistor is thermally coupled to the waveguide and reports medium temperature with +,- 0.2 degree C accuracy.

The waveguide electrodes are also used to measure the Electrical Conductivity of the medium. This property is also reported along with water content, permittivity and temperature.

For researchers who wish to perform their own unique analyses and experiments the TDR-315 can export TDR waveforms in csv format. The exported waveforms contain rich data relationships that can be used to determine other properties of the medium besides its permittivity and water content.

The device uses the standard SDI-12 interface, Version 1.3 and can be used with any Data Recorder or readout device that supports that standard.

The integration of the Time Domain Reflectometer into a single package provides several advantages over conventional high-performance TDR systems using a mainframe, coaxial cable and waveguide probe:

1. Conventional TDR systems use a TDR console coupled to a waveguide probe with a coaxial cable. An expensive high-performance coaxial cable is required to reduce the unwanted reflections from the impedance irregularities within the cable. Further the cable acts as a low pass filter that removes information from both the incident and reflected waves. The absence of the coaxial cable coupling the TDR electronics to the waveguide of the TDR-315 allows the full bandwidth of the step function generator to be applied to the waveguide and also facilitates an unfiltered capture of the reflected wave.

2. Conventional TDR systems cannot be deployed for continuous season-long field measurements without risking damage and a nuisance to crop managers. The TDR-315 can be completely installed in the root zone (without incurring root and compaction disturbances) and can remain there indefinitely. Soil tillage can be performed over the installation as long as the tillage depth does not reach within 2 inches of the sensor.

3. Power consumption of each TDR sensor is reasonably low allowing for low cost alkaline battery operation or rechargeable batteries coupled with a solar panel.

4. The cost of the TRD-315 is about 5% of the cost of a conventional TDR set capable of equivalent performance.

5. All measurements are performed automatically without the need for setting up the console, cable, probe, PC and software. The “first-principles-based” calculations are also performed automatically and the multiple data points are delivered within 2 seconds in industry standard metrics.

The advantage of the TDR-315 over capacitive, impedance and frequency domain sensors is one that is best explained by the fundamental physics behind the measurement. True Time Domain based sensors are designed to derive medium permittivity based on TEMPORAL measurements only. Voltages, currents, impedances, thresholds, etc. are avoided in the gathering of the physical properties from which permittivity is calculated. True Time Domain sensors are based in Ampere’s and Faraday’s Laws in a form known as the propagation equation. This equation states that if the propagation speed can be accurately measured, then the permittivity can be accurately known even under highly saline conditions. That measured permittivity can then be converted to water content through the Topp equation or a suitable dielectric mixing model. Using the propagation equation requires taking accurate time measurements on a waveform propagated through the soil. This requires very sophisticated electronics and techniques since the time measurements may be only trillionths of a second. In fact the TDR-315 can measure time intervals as short as the time it takes light to travel 1.5 mm in air.

Soil Electrical Conductivity is the killer of credibility in capacitive, impedance and frequency domain sensors. Although these sensors use widely differing architectures they are all based on deriving permittivity through measuring voltage and current relationships. This works well in non-conductive soils but when external ions, such as salts or fertilizers, are present those ions affect internal voltage and current magnitudes and relationships through Gauss' Law. Many of these sensors attempt to compensate for these EC effects but with marginal results. EC is a very strong function of water content and hence compensation of water content requires knowing water content. The TDR-315 by-passes the effects of Gauss' Law by avoiding any dependence upon the measurement of fields and fluxes. Only precise time measurements are made.

Installation and Connection:

The three wires from the sensor are the SDI-12 connections to the data recorder. The white wire is the common return or ground terminal on the data recorder SDI-12 connector block. The red wire is the power line and must attach to the power supply line on the data recorder SDI-12 connector block or to the positive side of an external power source. The blue wire is the bidirectional (half-duplex) data line that attaches to the serial data line on the data recorder SDI-12 connector block. If a power supply is used that is external to the data recorder then the negative side of the power supply must be attached to the ground terminal on the data recorder SDI-12 connector block.

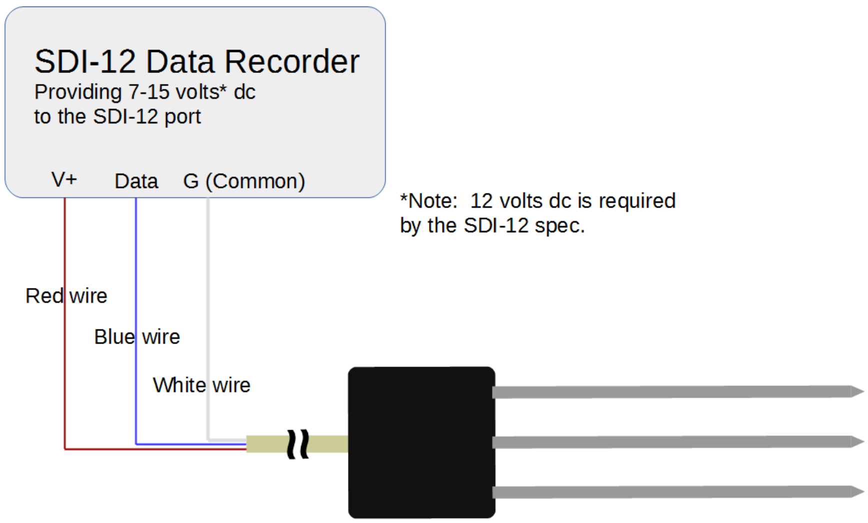


Diagram for a data recorder providing power to the SDI-12 port

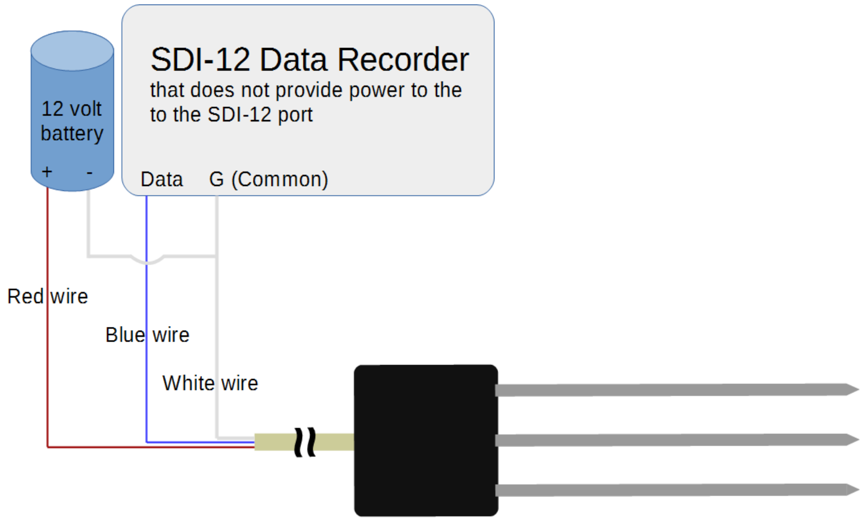


Diagram for the data recorder using an external battery

Operation:

The SDI-12 protocol allows multiple devices to be attached to one SDI-12 port. In order for the data recorder and devices to facilitate unambiguous communications each device on the SDI-12 port is given a unique address. The default address of the transducer (as shipped from the factory) is 0 (zero). If this is the only device on the SDI-12 port on the recorder then you may leave the address as 0. If other devices are connected then you will need to insure that they each have unique addresses. Setting the address will be discussed later.

SDI-12 commands are a concatenation of three fields. The first is the device address. This is a single character – typically in the range of "0" to "9" but can also use the characters "a" to "z" and "A" to "Z". The second is the command which may consist of several characters. The command characters are always upper case. The last is the command terminator which is always an exclamation point "!".

Command Summary:

The True TDR-315 sensor implements commands that comply with versions 1.0, 1.1, 1.2, and 1.3 of the SDI-12 specifications. All commands required for full compliance of the version 1.3 specifications are implemented in the TDR-315 sensor. However, the 'additional measurements' commands in the SDI-12 specification are meaningless to the Acclima SDI-12 sensors, since the permittivity, moisture, conductivity, and temperature measurements are all required and all made with every single measurement. Hence the response for all of these additional measurements commands is **"a<CR><LF>"** as required by the SDI-12 specification. The sensor ignores unimplemented commands outside those required by the SDI-12 specification. There is no response to them.

Additional 'Extended Commands' that are not enumerated here, are incorporated by Acclima for digitized waveform dumps and factory calibration settings and readings.

Command Reference:

The table below documents all commands supported by the SDI-12 sensor in alphabetical order:

Command	Function	Sensor Response
?!	Address Query	**a** Note: only one device can be connected to the SDI-12 port when this command is used. a<CR><LF>
a!	Acknowledge Active	**a** a<CR><LF>
aAb!	Change Address	**b** b<CR><LF>

Command	Function	Sensor Response
?!	Address Query	a Note: only one device can be connected to the SDI-12 port when this command is used. a<CR><LF>
a!	Acknowledge Active	a a<CR><LF>
aC! aCC!	Start Concurrent Measurement Start Concurrent Measurement-Request CRC	a00305<CR><LF> Measurement takes 3 seconds. 5 values are returned
aC1! . aC9!	Start Additional Concurrent Measurement	a00000<CR><LF> No data to be provided
aCC1! . aCC9!	Start Additional Concurrent Measurement – Request CRC	a00000<CR><LF> No data to be provided
aD0!	Get First 4 Data Items in response to a Measurement command: VWC, Soil Temp., Soil Permittivity, Soil EC Get the response from a Verify command	a + VVV.V + TT.T + PP.P + EEEE + CCCC<CR><LF> where: a = device address VW.V = volumetric water content % TT.T = soil temperature degrees C PP.P = soil permittivity EEEE = soil bulk EC in uS/cm CCCC = soil pore water EC in uS/cm

Data buffer Populated by:	Command Description	Response to "aD0!"
none/abort	No data generating command has been issued, or a command was aborted. Data buffer is empty.	a<CR><LF>
aM!	Fill data buffer with standard measurement	a+VVV.V+TT.T+PP.P+EEEE +CCCC <CR><LF> where: VVV.V = Volumetric water (%) TT.T = Temperature (°C) PP.P = Permittivity (no units) EEEE = Bulk electrical conductivity (uS/cm) CCCC = SOIL Pore Water EC (uS/cm)
aC!	Fill data buffer with standard measurement concurrently with other sensors	Same as aM!
aMC!	Fill data buffer with standard measurement and CRC check in the data response	a+VVV.V+TT.T+PP.P+EEEE+CCCC<CR><LF> where: VVV.V = Volumetric water (%) TT.T = Temperature (°C) PP.P = Permittivity (no units) EEEE = Bulk electrical conductivity (uS/cm) CCCC = Soil Pore Water EC (uS/cm)
aCC!	Fill data buffer with standard measurement concurrently with other sensors and with a CRC check in the data response	Same data as aMC!
aM1!	Fill data buffer with standard measurements	Same as aM!
aC1!	Fill data buffer with standard measurements concurrently with other sensors	Same as above
aMC1!	Fill data buffer with standard measurement and CRC check in the data response	Same as aMC!, except Bulk electrical conductivity (EEEE) is normalized to 25 °C
aCC1!	Fill data buffer with standard measurement concurrently with other sensors and with a CRC check in the data response	Same as above
aV!	Verify Sensor operation. This command produces the same result as the aM! Command	Same data as aM!

aD1! . aD9!		No data for this

Command	Function	Sensor Response
?!	Address Query	**a** Note: only one device can be connected to the SDI-12 port when this command is used. a<CR><LF>
a!	Acknowledge Active	a a<CR><LF>
aI!	Send Identification	**aSSVVVVVVPPPPPPcccxx...xx** **a13Acclima TDR315 1.3xx...xx** <CR><LF> ss= SDI-12 version 1.3 (2 ch) v= Vendor ID Acclima (8 ch) p= Product ID (6 ch) c= Product Version (3 ch) xx...xx= Serial Number (13 ch)
aM! aMC!	Start Non-Concurrent Measurement Start Non-Concurrent Measurement – Request CRC	**a0035**<CR><LF> Measurement takes 3 seconds and returns 5 values. **a**<CR><LF> Sensor returns a Service Request after measurement is made. The data can be retrieved using a aD0! command
aM! . aM9! aMC1! . aMC9!	Additional Measurements Additional Measurements – Request CRC	**a0000**<CR><LF> The SDI-12 sensor does not require the use of this command. If the command is received the sensor reports "no data" to be returned.
aR0! . aR9!	Continuous Measurement	**a**<CR><LF> The SDI-12 sensor does not use this command and responds with no data.
aV!	Start Verification	**a0031**<CR><LF> One data item will be returned after 3 seconds The data item will be the verification code requested by this command. **a**<CR><LF> The sensor returns a service request after the measurement is made. The data can be retrieved using a **aD0!** Command.

Setting the Address:

If more than one device is wired to the SDI-12 port you will need to assure that they all are set up with unique addresses. If you are not sure you can connect them one at a time and use the **"Address Query"** command **"?"** to read the addresses. Only one device can be connected to the SDI-12 port when using this command. The device will respond with its address.

To change the address of a device use the **"Change Address"** command. The syntax is **"aAb!"**, where "a" is the present address "A" is the Set Sensor Address command and "n" is the new address. The device will return the new address. For example, if **0A4!** Is transmitted, the sensor address will be re-programmed to 4 and the sensor will return "4".

To verify that the SDI-12 TDR sensor is responding to its address use the **"Send Identification"** command **"aI!".** The SDI-12 sensor will respond with "a13Acclima TDR315 1.3xx...xx" In the response the "a" is the device address, "13" represents Version 1.3 the SDI-12 standard and the "Acclima" is the vendor ID, TDR315 represents the sensor model, the next three characters report the firmware version of the TDR sensor, which is then followed by the serial number.

Making Measurements with the SDI-12 Sensor:

There are two commands that cause the SDI-12 sensor to take measurements and store them for subsequent retrieval. The first is the **"Non-Concurrent Measurement Command" "M".** The second is the **"Concurrent Measurement Command" "C".** The sensor responds to both of the commands with **"atttn"** where "a" is the sensor address, **"ttt"** is the number of seconds before the data will be ready, and "n" is the number of data items that will have been prepared. For the Acclima TDR-315 SDI-12 sensor the number of data items is 5.

Non-Concurrent Measurement:

When using the non-concurrent command, the recorder waits for the sensor to complete its measurement and then retrieves the result. The sensor sends a "Service Report" code to the recorder after preparing the data so that the recorder will retrieve the data at the appearance of the Service Request or after the indicated time has expired, whichever occurs first. The Service Request code is simply the address of the sensor "a", followed by carriage return and line feed characters.

Concurrent Measurement:

When using the concurrent measurement command the sensor does not return a service request when the data is ready for retrieval. The recorder is allowed to perform other communications to other devices while the sensor is making the measurement and preparing the data. Then when the recorder is available and the indicated measurement time has elapsed the recorder retrieves the data.

Data Retrieval:

To retrieve the requested measurement data the recorder sends a **"D0"** command to the sensor. The D0 command returns the basic 4 measurement items: Volumetric Water Content, Soil Temperature, Soil Relative Permittivity, and Soil Electrical Conductivity. The syntax for the command is: **"aD0!"**, where "a" is the sensor address. Below is a table showing the data available from the SDI-12 sensor and the commands used to retrieve them.

Data Item Request	Command	Response Example	Units
Volumetric Water Content	aD0!	+25.03	%
Soil Temperature	aD0!	+/-32.16	C
Bulk Relative Permittivity	aD0!	+32.13	--
Soil Electric Conductivity	aD0!	+1600	uS/cm
Soil Pore Water EC	aD0!	+1700	uS/cm

The format of the returned data is:

a+25.03+32.16+32.13+1600+1700<CR><LF>

Note that the returned data is always preceded by the device address **a.** Each data value is preceded by a sign. No units are returned but are assumed known by the user. The units are as shown in the table above. Each return data string is terminated by carriage return and line feed characters.

Examples of Using the TDR Sensor:

<u>Example 1: Reading sensors using non-concurrent commands:</u>

This first example shows how a data recorder would obtain 4 data items from a sensor that has address 5: (1) Volumetric Water Content, (2) Soil Temperature, (3) Soil Permittivity or Dielectric Constant and (4) Soil Bulk Electric Conductivity, and (5) Soil Pore Water EC. In this example the data recorder will operate in the non-concurrent mode – that is, it will not spend any time with other sensors until this sensor has completed its measurements and has reported them.

The first command from the data recorder is:

5M!

This command is called the "Start Measurement" command. The "5" in this command is the address of the sensor you wish to respond to the command. It will cause the SDI-12 sensor to begin the process of taking a set of measurements. The sensor will immediately respond to this command as follows:

50035<CR><LF>

This response starts with the address of the sensor (5), then continues with the number of seconds that are required to take the readings, **003** (3 seconds), then finished with the number of data items that will be returned with each measurement request (5). Every response from the sensor is terminated with a carriage return and line feed characters. After the sensor has finished its measurements it transmits a **service request** to the recorder.

5<CR><LF>

The **service request** is just the address of the sensor. The recorder then sends a command to get the first set of data items:

5D0!

The items requested are: volumetric water content, soil temperature, soil permittivity, and soil electrical conductivity. Upon receiving this command the sensor responds with:

5+25.03+32.16+32.13+1600+1700<CR><LF>

The first 5 is the sensor address. The remaining string contains the requested data items – each preceded by a "+" or "-" sign.

Example 2: Reading sensor using concurrent commands:
This second example shows how a data recorder would obtain the same 4 data items from a sensor using concurrent commands. In this example the data recorder will operate in the concurrent mode – that is, it will be free to service other sensors while the sensor with address 5 is making its measurements. Concurrent measurement commands use C instead of M in the command. Thus the command to start concurrent measurement is:

5C!

The sensor immediately responds with:

500104 <CR><LF>

With concurrent commands the sensor does not provide a **service request** after the measurements have been made. The recorder relies on the timing information provided by the sensor and will not request data until the time interval has expired – in this case 1 second.

The recorder then requests the four data items exactly in the same manner as with non-concurrent readings.

Data Communication Error Checking
So far, all **Start Measurement** commands that we have discussed have requested data wherein no error checking is done to verify the correct reception of the data by the recorder. The SDI-12 specification provides for error checking by using an additional command character "C" with the Start Measurement command. Thus when the commands

aMC! Or **aCC!**

are transmitted to the sensor, the sensor appends a CRC code to the end of the returned data. This code is generated from the data in such a manner that if the data changes in the transmission the change can be detected in the recorder. If the recorder experiences such corruption in the data it will repeat the data request automatically.

3.3.6 Verify Command
The SDI-12 specification requires a special command for the purpose of verifying that the sensor is working properly. Acclima's implementation of that command is as follows:

1. The recorder sends out the verify command:
aV!

2. Upon receiving the verify command the sensor will respond with:

atttn <CR><LF>

where “a” is the sensor address, “ttt” is the time required to make verification readings, and “n” is the number of data items that will be returned. For this command ttt = 003 and n=1.

3. The sensor takes 3 full sets of readings. The corrected propagation times from the three readings are saved and compared. If any of these propagation times are out range or if they differ by an unacceptable amount an error is acknowledged. The sensor then sends out a **service request**.

a <CR><LF>

4. The recorder issue a **read data** command **D0**:

aD0!

Accessing the TDR-315 Waveform:

The TDR-315 was developed as a Time Domain soil permittivity and moisture content measuring device but has application in many other research disciplines. TDR waveforms contain much more data than soil moisture content. Soil electrical conductivity can be accurately determined from them. Also other properties of the soil such as porosity and particle size have an influence on the characteristics of the waveform – hence it is appropriate to use TDR waveforms in characterizing these additional properties. The spectral content of the TDR-315 waveform is well preserved since there is no low pass filter between the waveguide and the digitizer. This provides an opportunity for high quality frequency domain analysis of the waveform that can yield additional characteristics of the medium.

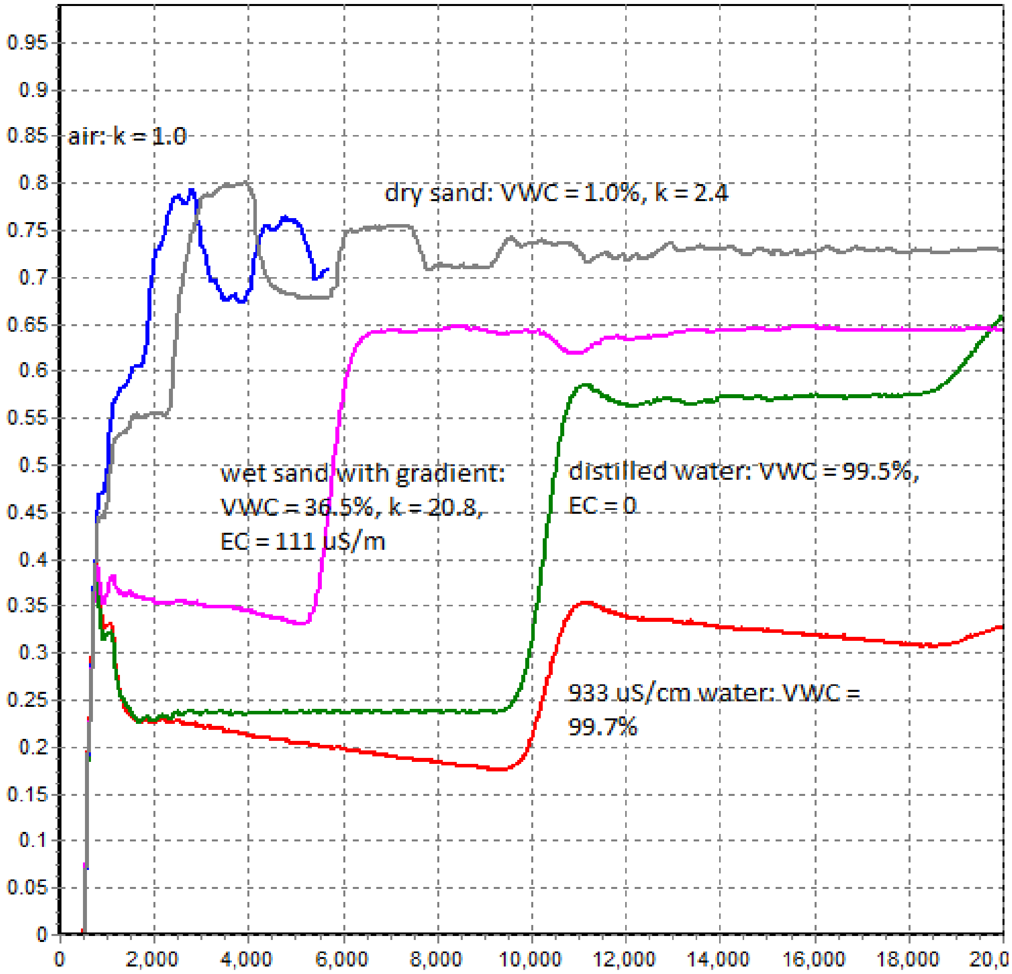
In order to support research using these enabling tools we have provided an extended SDI12 command that allows you to gather TDR waveforms from your subject media. The command is: **aXAtttt!**

Where ‘a’ is the device address, ‘XA’ is the extended command code, tttt is a hexadecimal time ordinate in 5ps units and ‘!’ is the command terminator. This command returns a hexadecimal string which represents the waveform amplitude at the ‘tttt’ time ordinate.

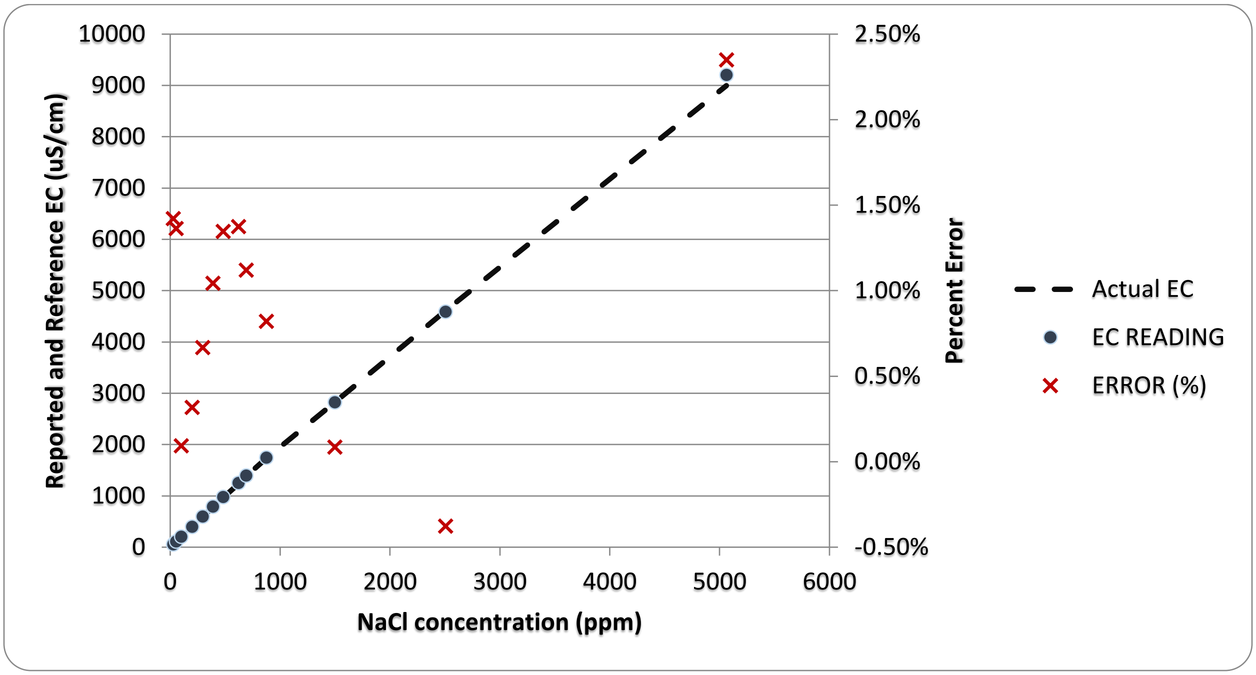
For Example:
If the amplitude of the waveform at 1100ps is desired it is necessary to convert the time ordinate to 5ps units or 220. This number is then converted to hexadecimal 220 decimal = 0DC hex. If the device address is ‘1’ then the following command is sent to the TDR-315: 1XA0DC!
The sensor returns the string: 18E6 <CR><LF> The first character (1) of the string is the device address. The other characters are the waveform amplitude at 1100ps. Note that the amplitude is normalized to a 12 bit binary number and must be divided by 4096. The return amplitude is then 8E6 hex / 4096 or 2278/4096 = 0.556.

You can write your own code to acquire successive points and thus get an entire waveform using this command.

The plot on the next page shows TDR waveforms gathered from several different media. The text over the waveforms shows the readings that were taken by the TDR-315 for each medium.



The EC measuring capability of the TDR-315 is based on Giese and Tiemann method for measuring EC with conventional TDR equipment. It provides high accuracy EC readings over a very wide range of conductivity. The chart on the next page shows the composite response from 20 TDR-315s compared to carefully prepared NaCl EC solutions at 25C. The 'tightness' of the response among the 20 sensors at each measured point was less than 1% rms deviation from the mean. The absolute accuracy of the mean reading at each point is shown on the plot with the 'X' marks. Note that the error of the mean reading relative to the standard is less than 1.5% from 0 to about 6000 uS/cm. At 9000 uS/cm the error is 2.4%.



Troubleshooting:

Problem	Possible Resolution
No Data Return by the SDI-12 sensor	Check the sensor connections to the data recorder. The white wire connects to the SDI-12 port Ground terminal. The blue wire connects to the SDI-12 port Data terminal The red wire connects to the SDI-12 port V+ terminal or to the positive terminal of an external battery. If an external battery is used the negative terminal of the battery connects to the ground terminal of the SDI-12 port.
Unreadable data	Insure that there are no address conflicts. Disconnect all other devices connected to the recorder. Insure that the sensor address is used in the commands you are using.
Sensor not communicating	Check connections Check Voltage Check address Review syntax
Unreadable data/parity errors	Insure that there are no address conflicts. Disconnect all other devices and try to read again. Insure that the cable length to the sensor does not exceed 200 feet.

Specifications:

Physical Characteristics:

Dimensions (without cable)	20 cm x 5.33 cm x 1.9 cm
Weight (with 10 meter cable)	440g
Composition	Type 304 stainless steel, epoxy, polyethylene (insulation)
Cable	3 conductor, 22 Ga., Water proof and UV resistant PVC jacket, 10 meters

Environmental Characteristics:

Operating Temp Range	-20 C to 50 C

Storage Temp Range	-20 C to 75 C

Operating Characteristics:

Volumetric Water Content	0 to 100%
Resolution	0.1% VWC
Absolute VWC Accuracy	+/- 2% typical
VWC Temp Stability	+/- 1% of full scale 1 C - 50 C
VWC Soil EC Stability	+/- 2% of full scale 0 to 5 dS/m BEC
Temp Reporting Accuracy	+/-0.2 C 0 to 50 C
EC Reporting Accuracy	+/- 2.5% 100uS/cm 0 to 10,000 uS/cm BEC

Architectural Characteristics:

Technology	Waveform Digitizing Time Domain Reflectometer
Effective Acquisition Bandwidth	200 Giga-sample/sec.
Propagation Time Resolution	5 ps
Waveform Propagation Resolution	1.5 mm in air, 0.16 mm in water
Waveguide Length	15 cm
Permittivity to VWC Calculation	Modified Dielectric Mixing Model
Propagation Waveform Bandwidth	3.5 GHz

Communications Characteristics:

Communication Protocol	SDI-12 Revision 1.3
Maximum Cable Length	60 meters
Maximum Devices per Cable	50

Power Characteristics:

Operating Voltage Range	6 – 15 VDC
Listening/Sleep Mode Current	31 uA typical, 35 uA max
Communications Current	4 mA typical, 5 mA max
Read Moisture Comm Time	425 ms total for each read cycle
Moisture Sense Current	180 mA at 12 VDC input 300 mA at 6 VDC input
Moisture Sense Time	2.2 seconds

Notes:

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