User Manual for the

WET150 sensor

SDI-12

Delta-T Devices

Notices

UKCA conformity

The WET150 Sensor conforms to UK regulations regarding electromagnetic emissions and susceptibility when used according to the instructions contained within this user manual, and is UKCA marked by Delta-T Devices Ltd

CE conformity

The WET150 Sensor conforms to EC regulations regarding electromagnetic emissions and susceptibility when used according to the instructions contained within this user manual, and is CE marked by Delta-T Devices Ltd

FCC Emissions

CFR47 Pt 15 B [Unintentional Radiator emission limits as per Pt 15.109]

Note: This equipment has been tested and found to comply with the limits for a Class A digital device, pursuant to part 15 of the FCC Rules. These limits are designed to provide reasonable protection against harmful interference when the equipment is operated in a commercial environment. This equipment generates, uses, and can radiate radio frequency energy and, if not installed and used in accordance with the instruction manual, may cause harmful interference to radio communications. Operation of this equipment in a residential area is likely to cause harmful interference in which case the user will be required to correct the interference at their own expense.

Design changes

Delta-T Devices Ltd reserves the right to change the design and specification of its products at any time without prior notice.

Patents

The WET150 is protected under international law by the following:-

USA: Patent US7944220

Europe: Patent EP1836483

Australia: Patent AU2005315407

China: Patent CN101080631

Contents

Getting Started

Thank you for purchasing the WET150, Delta-T's robust and accurate sensor for water content, electrical conductivity and temperature. To ensure you get the most out of your sensor, we recommend the following steps:
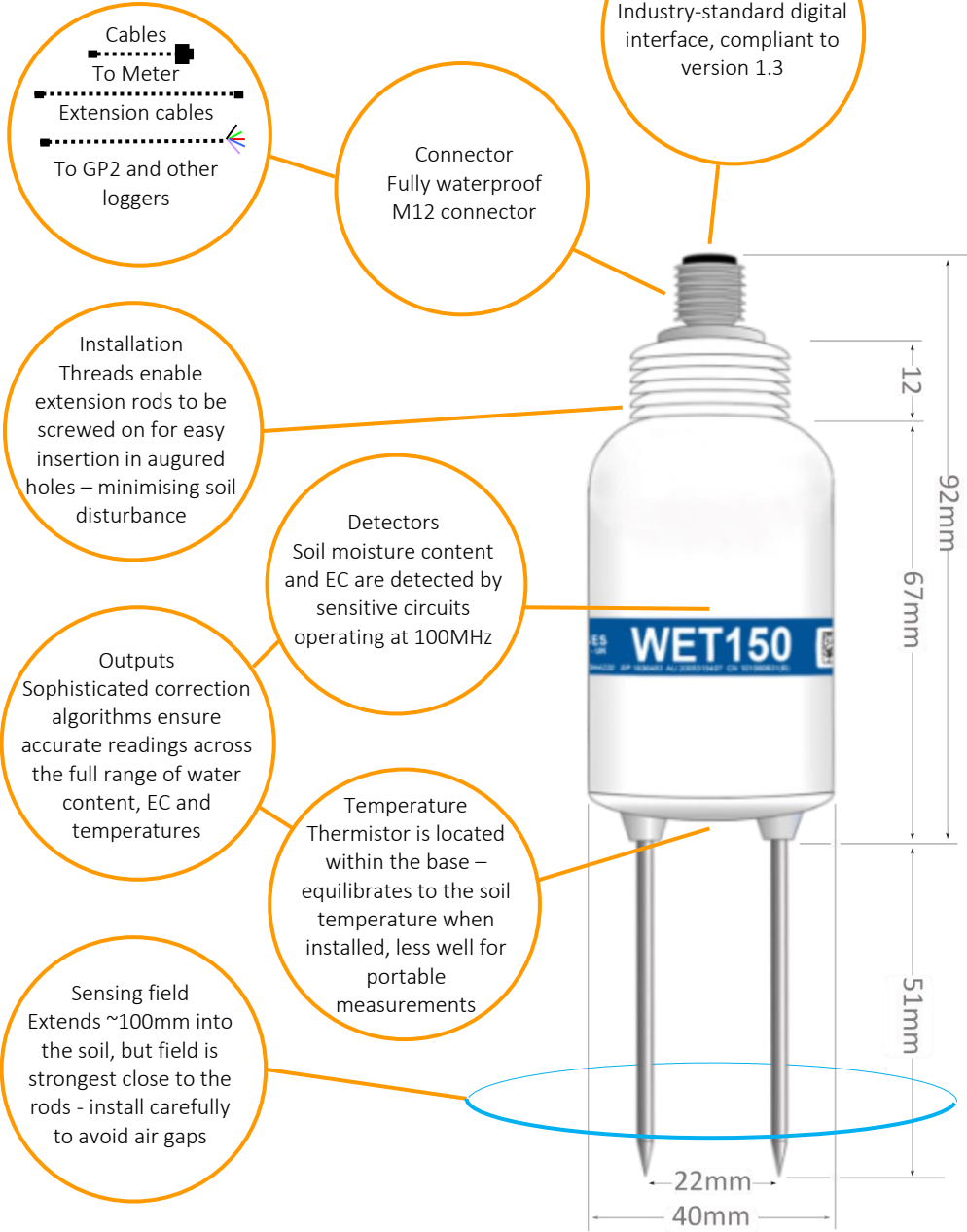
1. **Check you have all the equipment you need.**
   For a list of accessories and additional equipment see section "Parts and Accessories".
2. **Check your sensor is properly configured for your intended use.**
   The WET150 is highly customisable to ensure maximum effectiveness in a wide variety of applications. See section "Configuration".
3. **If using with the WET150 Meter:**
   See section "Use with a WET150 Meter"
4. **If using in a permanent installation:**
   a. Check how to connect your sensor - See section "Connecting to Loggers & Controllers".
   b. Check how to install your sensor See section "Installation in the Ground".

5. **Review the care and maintenance requirements of your sensor.**
   See section "Care and Maintenance".

Care and Safety

- The pins of the WET150 are sharp. Care must be taken and handling precautions followed.

- Avoid touching the pins or exposing them to other sources of static charge, particularly when powered up.
  Keep the WET150 in its protective package when not in use.

To prevent personal injury and damage to the probe always store and transport in this carton

CAUTION SHARP PINS
Handle with care

ATTENTION
OBSERVE PRECAUTIONS FOR HANDLING ELECTROSTATIC DEVICES

- Take care when attaching cables to ensure that the connectors are clean, undamaged, and properly aligned *before* pushing the parts together.

- Do not pull the WET150 out of the soil by its cable.

- If you feel strong resistance when inserting the WET150 into soil, it is likely you have encountered a stone. Stop pushing and re-insert at a new location.

- WET150 is unsuitable for use in hard soils unless holes are pre-formed. Rough handling may cause irreparable damage to the pins

Introduction

Cables
To Meter

Extension cables

To GP2 and other loggers

Connector
Fully waterproof
M12 connector

SDI-12
Industry-standard digital interface, compliant to version 1.3

Installation
Threads enable extension rods to be screwed on for easy insertion in augured holes – minimising soil disturbance

Detectors
Soil moisture content and EC are detected by sensitive circuits operating at 100MHz

Outputs
Sophisticated correction algorithms ensure accurate readings across the full range of water content, EC and temperatures

Temperature
Thermistor is located within the base – equilibrates to the soil temperature when installed, less well for portable measurements

Sensing field
Extends ~100mm into the soil, but field is strongest close to the rods - install carefully to avoid air gaps

WET150

12

92mm

67mm

51mm

22mm

40mm

Description

The WET150 Sensor is a multi-parameter sensor for use in soils, substrates and other growing media. It measures the dielectric properties of the soil and calculates:

- Water Content
- Electrical Conductivity
- Temperature

The sensor converts the measured dielectric properties into Water Content over the full range, 0 to 100%, being most accurate over 5 to 100% water content and over 0 to 500 mS/m soil bulk conductivity[1]. Generalised calibrations are provided for most common soil types.

The WET150 Sensor also measures the bulk electrical conductivity of soil (EC_b) over 0 to 2000 mS/m, being most accurate, ±(10 mS/m + 6%), from 0 to 1200 mS/m.

It also calculates Pore Water Conductivity, the electrical conductivity of the water within the pores of the soil (EC_P).
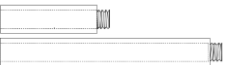
Temperature is measured by a miniature sensor built into the body of the sensor.

The WET150 Sensor works with the WET150 Meter and the GP2 logger controller. It can also be used with other SDI-12 loggers, and with SDI-12 fertigation and irrigation control systems.

Advantages of the WET150 Sensor

- Fast, accurate, adaptable and easy to use
- Rapid measurements (<0.5 seconds) of all 3 parameters
- *In-situ* Pore Water Conductivity measurements
- Easy insertion into growing media and soil
- Works with many different soils and growing media
- Stable, accurate readings from
- 5 to 100% water content
- 0 to 1200 mS.m^{-1}
- -20 to +60°C
- Lightweight ergonomic design
- Versatile SDI-12 digital output
- Systems integrator friendly
- Wide choice and customisable settings, outputs and units
- Low power for long battery life
- 2-year warranty extends to 5 years if registered on delivery

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[1] Best accuracy is achieved with a calibration matching the soil / substrate

Parts and Accessories

	WET150 sensor	
	WET150 Kit	WET150 + WET150 Meter
	SMSC/lw-05	5m cable with 200 mm flying leads. Connects WET150 to GP2 directly, or via SDI-12 network of EXT/5W-xx cables
	EXT/5W-01 EXT/5W-05 EXT/5W-10 EXT/5W-25	1 m, 5 m,10 m and 25 m extension cables with 5-way M12 connectors. Connects WET150 to an SDI-12 sensor network
	GP2-STP1	4-pin network T- Piece for networking of SDI12 sensors and EXT/5W-xx cables. **Not to be used for logger communication networks.**
	GP2-NTP	5-pin network T- Piece with continuous screen, for connection of loggers and EXT/5W-xx cables.
	ML/EX50 ML/EX100	Extension tubes, 50 and 100 cm
	SM-AUG-100	Spiral Auger 1.2 m

Use with a WET150 Meter

The WET150 Meter Kit enables portable monitoring of water content, electrical conductivity and temperature. It can also be used to change the address of an SDI12 sensor.
Settings for soil type, conductivity units and temperature units can be customised.

For more details see the WET150 Kit Quick Start Guide.
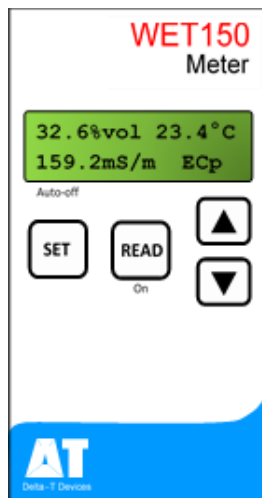
Take a Reading

READ
1. Gently insert WET150 pins into soil or substrate.
2. Press READ to take and display water content, temperature and pore water conductivity.

Options

Water content can be displayed as volumetric water content (%) using the Mineral, Organic, Peat mix, Coir, Mineral wool or Custom[2] calibrations; or the meter can display the RAW (unconverted) permittivity reading (ε') which has no units.

Temperature can be displayed in °C or °F.

EC is displayed as the pore water conductivity, EC_p, in mS.m^{-1}, for the chosen soil type; or the soil bulk conductivity, EC_b, when the RAW display option is selected.

Address can be a to z, A to Z or 0 to 9 (0 is not advised on a network)

WET150 Meter Buttons

READ

SET

READ – takes and displays a reading.

SET shows the settings menu. You can scroll up or down through these options: Soil type, Units and Address and Contrast... Press SET to select the highlighted menu and show the current setting in that menu. Again, scroll up or down and press SET to confirm the choice and return to the start-up screen. Alternatively, press READ to save the setting, exit the menu and take a reading.

▲ and ▼ scroll through the current options.

Auto-off - after 1 minute saves the current selection and switches off.

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[2] Please note customisation in the Meter does not change settings stored in the sensor; see section "Configuration", page 39

Using the WET150 Meter to Change Address

The WET150 Meter can only take and display readings from WET150 sensors. However, it can display and modify the address of most SDI-12 sensors with a compatible power requirement.[3] In order to connect to a WET150 Meter, the sensor would need to be fitted with an M12 connector – see section "Non-Delta-T loggers and systems wiring" on page 11.

> ! Each sensor must have a different address on an SDI-12 network or the network will not function properly. The address must be set BEFORE attaching to the network. !

You can use this key stroke sequence on a WET150 Meter to change the SDI-12 address of any attached SDI-12 sensor, including WET150 or PR2s. Only attach one sensor at a time to a WET150 Meter.

1. Press [SET] to wakes the Meter and displays the settings menu
2. Press [▼] twice to scroll down to the Address setting menu
3. Press [SET] to select that menu, and display the current SDI-12 address
4. Press [▼] or [▲] to scroll to the desired target address
5. Press [SET].

The Meter attempts to set that address:
   ▪ Success is indicated by the brief appearance of the ✓ symbol, after which it reverts to the Settings menu.
   ▪ Failure is indicated by ✖, after 3 seconds it reverts to the Address setting menu.

See also WET150 Kit Quick Start Guide

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[3] The Meter can supply approx. 100mA at 6 volts to an attached sensor

Connecting to Loggers & Controllers

The WET150 is fully compliant with the SDI-12 communication protocol standard (version 1.3). Because of this the WET150 can be used with any third-party logging or metering device which is also SDI-12 compliant as well as with Delta-T Devices GP2 logger controllers.

Wiring

GP2 Logger Wiring: See pages 12 and 13

Non-Delta-T loggers and systems wiring

Wire colour		Logger or controller	SDI-12 function	M12 connector pin
Brown		Not connected		1
White		+12V 0.5A	Network power	2
Blue		GND	Ground (for power and data)	3
Black		DATA	Data (send and receive)	4
Grey		Not connected		5
Green		Not connected **	(Cable screen) **	Shell / nut

** Optional. The green wire is connected to the cable screen. The SDI-12 specification does not require the green wire / cable screen connected. If there is a lot of electrical noise in the environment, connecting the green screen wire to ground in the logger or controller may help reduce the risk of data corruption. Note that for a continuous screen connection it is necessary to use the NTP T-piece.

For other connection details to third-party loggers and controllers please consult the SDI-12 sections of those products' manuals.

For SDI-12 screw terminal cable connector information see the SDI-12 for GP2 User Manual. See also "Power supply and communication" on page 23
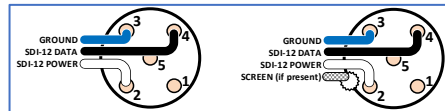
If ECp and water content values are being returned from the WET150 sensor, remember to review the soil parameters and adjust them if required – see section "SDI-12 commands" (page 28), and the WET150 SDI-12 Programmer's Guide.

GP2 wiring (1): Using internal power

The GP2 logger controller incorporates a program-controlled power rail specifically for SDI-12 applications. This 12V supply is generated from the internal logger battery pack via a voltage step-up circuit and is current limited in case of faults on the SDI-12 network.

SDI-12 sensors typically require a 3-wire connection: Power, Ground and Data. This is the case with the WET150 but the cabling system includes additional wires which are not normally used within an SDI-12 network.

To create an SDI-12 network based upon a GP2 logger controller, use cable type "SMSC/lw-05" to bring the network connections out of the GP2 case. This is a shielded 5-way, 5-metre-long cable with bare wires on one end and a 5-way M12 connector on the other. Use this to connect one WET150 directly to a GP2, or with the addition of other 5-way M12 extension cables and T-pieces, connect multiple sensors in a network.

Wire colour	GP2 terminal (SDI-12 block)	SDI-12 function	M12 connector pin
Brown	Not connected		1
White	+12V 0.5A[4]	Network power	2
Blue	GND	Ground (for power and data)	3
Black	DATA	Data (send and receive)	4
Grey	Not connected		5
Green	Not connected**	(Cable screen) **	Shell / nut

** Optional. The green wire is connected to the cable screen. The SDI-12 specification does not require the green wire / cable screen to be connected.

If there is a lot of electrical noise in the environment, connecting the green screen wire to the GND terminal (with the blue ground wire) in the GP2 may help reduce any risk of data corruption. The figure on the right illustrates the wire and terminal connections with the optional green screen wire.

SDI-12 DATA
GROUND
SDI-12 POWER
SCREEN
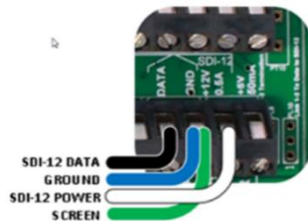
The brown and grey wires in cable type "SMSC/lw-05" are not normally required for SDI-12 so should be insulated from shorting to any terminals inside the GP2, or they may be trimmed off. The same applies to the green screen wire if it is not used.

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[4] 0.5A assumes good quality alkaline AA cells are used in the GP2. Other battery types may deliver lower maximum current drain.

Power is automatically supplied when the WET150 sensor is selected in the DeltaLINK program.

GP2 wiring (2): Using external power

The WET150 is a highly energy efficient sensor. Depending upon the measurement frequency and the number of WET150 sensors in the network, the internal GP2 logger/controller batteries are capable of providing power for many tens of thousands of sensor readings over periods longer than a year.

If the WET150 is used in conjunction with other more power-hungry SDI-12 sensors, it may be desirable to use a larger external power supply for the SDI-12 network. The functioning of the GP2 logger/controller itself can remain running on its own internal batteries independently of an external power source for the SDI-12 network.

To use an external power supply for the SDI-12 network, do not connect anything to the GP2's "+12 0.5A" power terminal. Instead wire the SDI-12 network power (white wire on cable type "SMSC/lw-05") to the external power source +12Vdc terminal.

Wiring connection diagram showing external SDI-12 power connections for the SDI-12 network, along with the optional green screen wire.
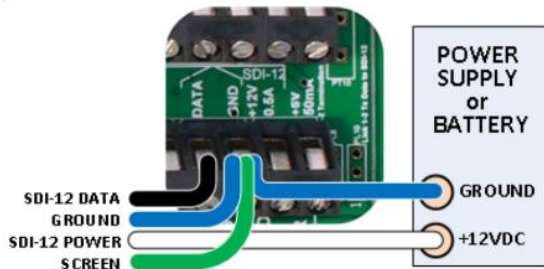
Ensure there is a fuse or other protection in-line with this external power source in case short-circuit faults develop on the SDI-12 network.

The Ground or 0V terminal of the external power source should be wired into the GND terminal on the GP2, along with the Ground wire of the SDI-12 network (blue wire on cable type "SMSC/lw-05").

In the external power supply configuration shown above, power is permanently applied to the SDI-12 network. This may not be the most desirable or efficient way to run the network. An alternative would be to wire one of the GP2 internal relays in series with the external power supply and the SDI-12 network power wire.

The GP2 logger/controller program can then be configured to switch in the power only when taking measurements for greater external power efficiency.
e.g In DeltaLINK program's Measurement, Power channel select RLY1.

Assigning Addresses using a GP2

If two sensors have the same address, then neither sensor will be able to communicate and the SDI-12 network may not function. Each WET150 MUST have a unique address before connecting it into a network of SDI-12 sensors.
The address of a new sensor is usually 0 (number zero). It can be changed to any single digit address in the range 0 to 9, a to z or A to Z.
Use either a WET150 Meter connected directly to a WET150 sensor - see page 5, or use a GP2 and PC running DeltaLINK as described below.

Install DeltaLINK

To operate the functions of the GP2 logger/controller, its companion computer software "DeltaLINK" needs to be downloaded and installed. This PC software is available from the Delta-T website at:

www.delta-t.co.uk/software/deltalink

DeltaLINK version 3.9 or later is required for use with the WET150. If your existing install of DeltaLINK is older than this version, please install the latest version to gain access to WET150 libraries.

DeltaLINK is available for Microsoft Windows only.

Once DeltaLINK is installed, connect the GP2 to your PC computer using the USB to GP2 cable supplied with the GP2.

See also:

- GP2 User Manual
- SDI-12 for GP2 User Manual
- WET150 SDI-12 Programmer's Guide

1: Open DeltaLink Transparent Mode

You need a GP2 connected to a PC running DeltaLINK v 3.9 or later.

With no other sensors on the network connect the sensor to the GP2 SDI-12 terminal.

In DeltaLINK select Tools, SDI-12, Transparent mode to open theSDI-12 Transparent Mode Terminal as shown below.
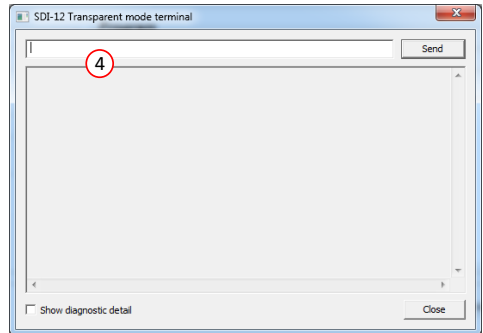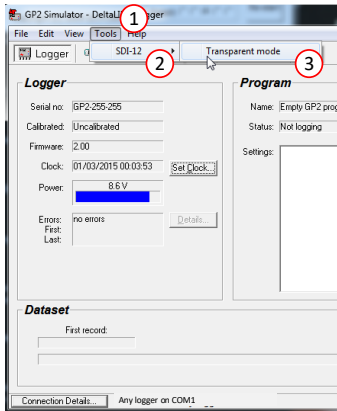
Once the SDI-12 Transparent Mode Terminal is open, the GP2 behaves like a transparent serial link between SDI-12 sensors and the PC.

2: Find out WET150's current address

Send a command to tell the sensor to reply with its address.

Example:

You type	?!
Reply	a

We usually expect the address of a new sensor is to be zero, but it might not be. If you already have another sensor with the same address on the same network the command will not work.

3: Change the address

Send a command to change its address

You type	aAb !
Reply	b

The WET150 is now at address **b**. It could be anything from **a** to **z**, **A** to **Z**, or **0** to **9**. Avoid address 0 as it tends to be the default used in new sensors. Any sensors which share the same address on the network will be unable to communicate.

Make a note of the address and the serial number. Clearly labelling the sensor (or attached cable) will make setting up and troubleshooting much easier later on.

Later when you have finished giving each sensor a unique address, close the Transparency Mode window and change the default GP2 program to create a WET150 sensor type measurement with the correct address, and repeat this for each sensor to go on the network.

Tip for advanced users:
You can change the default Measurement Name to add useful metadata - for example, by adding the address as a suffix so that *Theta* becomes *Theta Z*. But the ECp calculation also uses the Permittivity and SoilTemp readings. So, in the Calculation section of the ECp Measurement parameters change the Permittivity name e.g. from *Theta* to *Theta Z*   and likewise for the Temperature name if you have also changed that, e.g. from *SoilTemp* to *SoilTemp Z*.
If you change Measurement name you must also change the Recording Rate entry to match.

Create GP2 Program

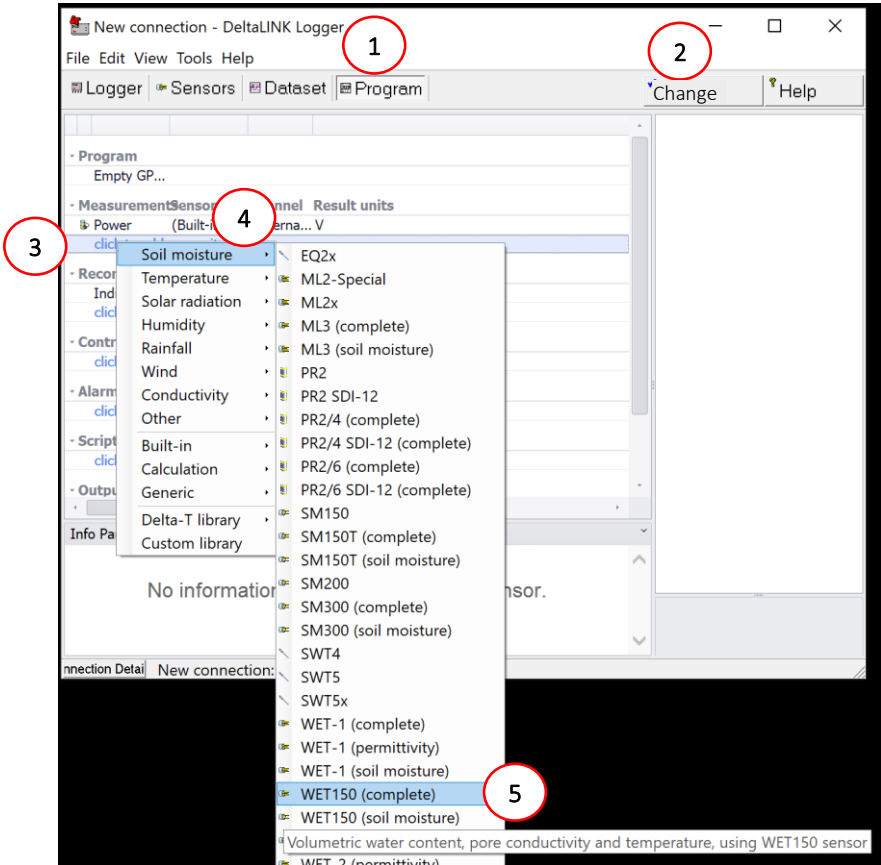## 1: Add a WET150 SDI-12 Measurement

Illustration: showing steps in the creation of a WET150 soil moisture sensor measurement type in a GP2 program.

1. With DeltaLINK 3.9 or later running on your PC and connected to a GP2 select Program.
2. Select Change.
3. Under Measurements click on "click to add a new item".
4. Select Soil Moisture.

5. Select WET150 (complete). This will create three sensor measurement types for soil moisture, electrical conductivity and temperature, each with a default 1 hour recording period.
6. Select the Address to that of the WET150 sensor, as described on page14.   You should now see the following:
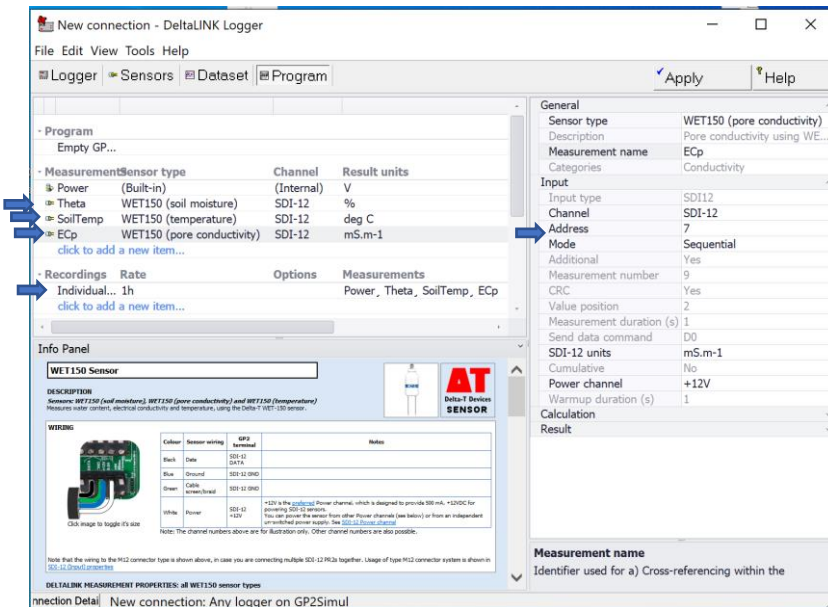

Illustration showing three sensor measurement types added to take readings from a single WET150, for soil moisture, pore water conductivity and temperature. These all have the same SDI-12 address, which in this example has been changed to 7 from the default 0 address. The default measurement period of 1 hour for all readings can be also seen.

2: Sensor type Settings

This explains the Measurement and Parameter settings supplied in the WET150 sensor types in the DeltaLINK sensor library.

1. **Sensor type**: This is the name of the default WET150 Sensor type as loaded from in the GP2 sensor library.

2. Change the **Measurement name** to anything useful e.g Theta (100mm) or Treatment A.

   If you have more than one WET150, give each measurement a unique name here – e.g. "ECp at 100mm". This information will be displayed at the top of the column of measurements in the results table.

   If you change a Measurement name then ensure it is updated in the Recording Rate. (The program will object and fail to "Apply" if you don't do this).

   Also if changing the WET150 Theta or SoilTemp Measurement names you will need to use the same names used in the ECp Calculation section.

   Example: change the Measurement name to add useful metadata e.g. *Theta* becomes *Theta Z* to display the address in the results. The ECp calculation needs to use the Permittivity and SoilTemp readings. So, in the Calculation section of the ECp Measurement parameters, change the Permittivity name from *Theta* to *Theta Z*   and likewise for the Temperature name, if you have also changed that, e.g. from *SoilTemp* to *SoilTemp Z*.

Showing the addition of address Z to the WET150 Measurement names
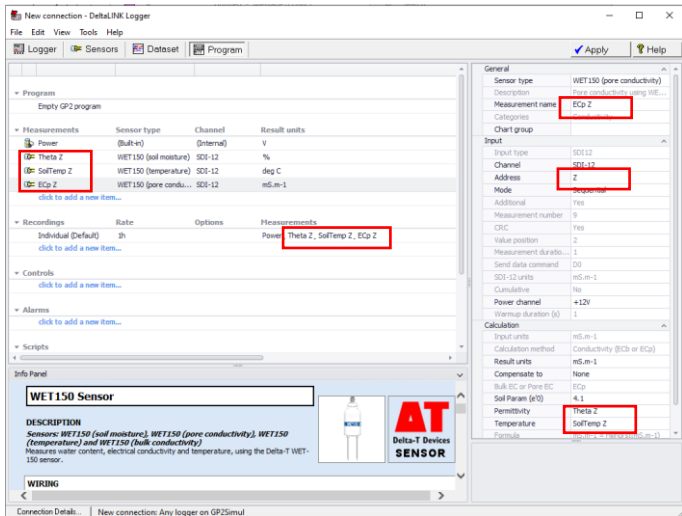
3. **Address**: Enter the WET150 address so the GP2 will know which sensor to contact. You must do this.
   Use DeltaLINK, SDI-12, Transparent mode (or a WET150 Meter) to give it a unique address before putting it on the SDI-12 network with other sensors, or else the network will crash.
   See also Assigning Address on page 14.
4. **Mode**: The default WET150 sensor type uses the SDI-12 Sequential data measurement and reporting method.
   See also Concurrent Measurements on page 24.
5. **Additional**: No action required. The default value cannot be changed. The additional features are of use to less capable loggers from other manufacturers, which can't do maths as well as the GP2).
6. **Send data Command**: No action required. Your GP2 logger knows which D command to send, so this is not something you need to worry about.
   (Note for other logger users: The Dn command is sent by the logger to retrieve the results when the sensor is ready (n can be 0 to 8). In reply the sensor may send up to 76 characters to the logger. The number of characters required for each reading can vary: depending, for instance, on whether readings are concurrent or sequential. So additional commands, D1–D8, are available if necessary.
   See also WET150 SDI-12 Programmers Guide)
7. **SDI-12 units**: options:
   Soil moisture: % or m3.m-3.
   Pore water conductivity: $mS.m^{-1}$ $mS.cm^{-1}$ or $\mu S.cm^{-1}$
   Temperature: °C
8. **Soil type**: options:
   Coir, Mineral Soil, Mineral Wool, Organic soil, Peat Mix, or add your own soil type coefficients.

3: Set Recording Intervals

On selecting a measurement, DeltaLINK automatically sets a default recording interval, of one hour, as shown below.
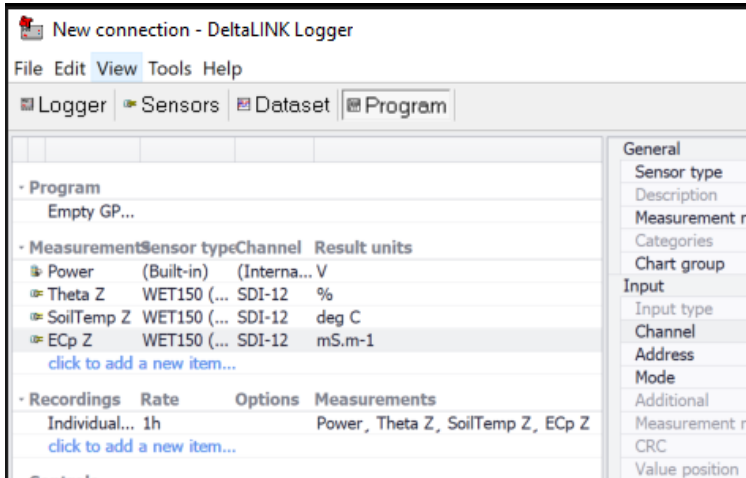

Illustration: DeltaLINK, GP2 Program tab with a default Recording interval set to 1 hour for each of the defined Measurements.

Chose a recording interval appropriate for your soil type.
For instance, if sandy it may drain quickly, in which case the fastest recording rate possible is about once every 5 seconds for one WET150 on a GP2. (62 sensors may take 50-55 seconds in the standard, sequential mode). In a heavy clay you may wish to start recording once per hour and wait and see how quickly the soil responds to wetting and drying events.

4: Next Steps
- Click on Apply to install the program in the logger.
- Select the Sensors tab and click on Read now to see the WET150 readings.
- (Please note the GP2 Simulator does not work with SDI-12 sensors)
- Select the Logger window and Start to start logging…
- Select the Dataset window from which you can Retrieve and display all stored readings.

  See also the SDI-12 for GP2 User Manual.

Networking
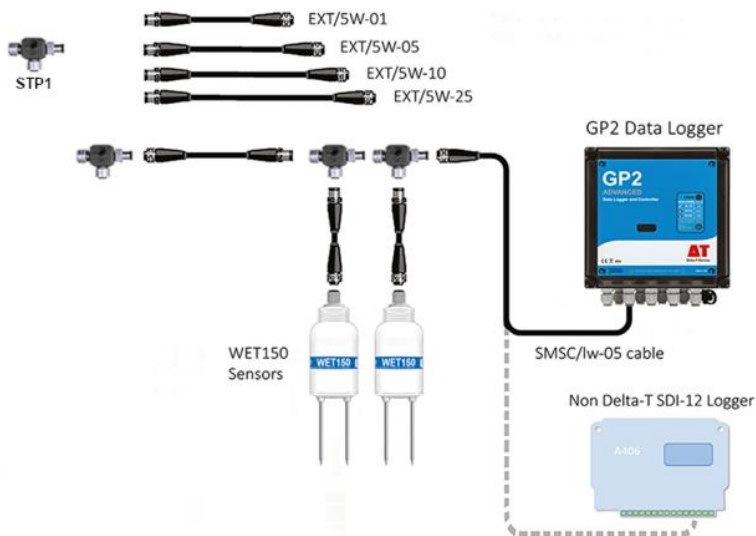
One WET150 can be read with a WET150 Meter. Multiple WET150s need a GP2 or other SDI-12 controller.

Delta-T extension cables are terminated in M12 thumb-screw connectors. Other cable types can be used, but this system has several advantages. Cables can be joined together to extend runs, or can be connected via a T-piece to branch the network and to connect to sensors. The M12 connector system makes it quick and easy to build and modify SDI-12 networks. Later if a network fails due to a faulty sensor or damaged cable, it is easy to isolate sections by temporarily disconnecting network branches or individual sensors to trace the fault.

M12 connectors on cables and the WET150 are waterproof to an IP rating of IP68, but must be screwed together tightly to form this waterproof seal. Failure to sufficiently tighten the collar may allow water ingress into the cable or sensor, leading to premature failure which is not covered by warranty. However, we do not recommend tightening with a spanner or other tool as there is a risk of overtightening and damaging the o-ring seal.

M12 plugs with screw connectors (also known as "field-attachable connectors") are available for adding other sensors to the SDI-12 network.

Before connecting on a network each WET150 sensor must be individually set up with a unique address. To do this they must be individually connected to either to a GP2 logger controller, or WET150 Meter or other SDI-12 controller.

This is also a good opportunity to change individual sensor parameters, e.g. for soil type

See also: SDI-12 for GP2 User Manual

Maximum cable length and network size

The SDI-12 standard requires that a cabled sensor network with a logger must be capable of supporting at least 10 sensors, each with 200 feet (61m) of cable in a star configuration back to the logger. It also states that longer cable lengths are possible if the network contains fewer sensors.

However, there is no defined maximum individual or total cable length as this depends on many factors including the numbers of sensors, network configuration, supply voltage, cable type, logger type and environmental factors (such as whether the cable is buried) and proximity to electrical noise sources like transmitters and power transformers.

While it is not possible to test every network configuration, tests have been carried out on various configurations with different cable lengths and numbers of WET150s. One such scenario was fifteen WET150 sensors daisy-chained 5m apart using extension cables and T-piece connectors, all on a single 245m backbone (320m in total).

The theoretical maximum number of sensors on any SDI-12 network is 62, as defined by valid address ranges 0-9, A-Z, a-z. Tests so far have shown that at least 35 WET150 sensors can be connected to one GP2 logger/controller. The test was performed using a star configuration with each WET150 connected using 2m cables.

If the SDI-12 network also contains devices other than the WET150, a reduced maximum number of sensors or reduced overall cable length may be needed due to their potentially higher network loading

Power supply and communication

The WET150 operates from a 6 to 20 Volt DC power supply. Power can be applied continuously, or for greater battery economy just as needed when taking measurements.

The power, ground and SDI-12 data pins all have protection against accidental reverse voltage or mis-wiring of the connections up to 24 Volts.

Current consumption per WET150 (typical values when powered from 12 Volts):

1. Idle / standby (no SDI-12 network activity): <0.5mA

2. SDI-12 network activity: 1mA

3. Active sensing: 22mA average over 12ms (average value includes contributions from short peaks at 45 to 90 mA, dependent upon network and power supply impedances)

4. Active computation: 2mA over 200ms

The GP2 logger controller provides a regulated 12 VDC output at 500 mA from its internal batteries. This power rail meets the SDI-12 specification and can be switched on and off under program control. It is ideal for powering multiple WET150s and other low power SDI-12 devices on a network.

If not using the internal GP2 12 Volt supply, it is recommended that the external power supply has a minimum short-term current capability of 85mA + (5mA per WET150 on the network) for both sequential and concurrent measurements.

If the GP2 must supply significant power to other types of sensors or accessories, we recommend powering the sensors from an external power supply, which can be switched via a GP2 relay under program control.

Warm-up time

If the SDI-12 network is powered down between measurements for greater battery economy, a warm-up time should be included in the logger program at the start of each measurement block. The warm-up time allows the micro-controller in the sensor to boot up and prepare to receive SDI-12 commands. The length of warm-up time depends on the type of sensor, the slew rate of the system power supply and the size of the network.

For a WET150 using the internal GP2 logger 12V power rail, the total power-up and boot time is less than 100ms, even with up to 26 WET150s connected together in a small network. The shortest GP2 warm-up setting is 1 second, so use this value in the GP2 program.

Multiple WET150s in a network

Sequential measurements

One WET150 is instructed to take a measurement and then return its results before moving onto other WET150s in the network.

Only one WET150 is fully active at a time. All the others are either in SDI-12 network activity mode when the data line is active, or idle mode when it is not.

Concurrent Measurements

All WET150s in the network are individually instructed to take a measurement as soon as possible without waiting for any other WET150. They then hold their measurement results until the logger requests them from each sensor individually in sequence.

Due to the short active sensing time of the WET150 and the slow communication speed of SDI-12, in practice, only one WET150 in a network is actively sensing at any given time even when using concurrent measurements. The worst-case

scenario is that one WET150 is actively sensing whilst another is actively computing and all others are in SDI-12 network activity mode. Therefore, the maximum network current demand during a concurrent measurement is little more than if performing a sequential measurement.

Care should be taken when performing concurrent measurements if sensors other than the WET150 are also used in the network. Their sensing time and power supply current demands may be greater than the WET150, which could limit the total allowable number of sensors within a concurrent measurement group.

See the SDI-12 for GP2 User Manual for more information on using groups with concurrent measurements to prevent network power supply overloading.

Data communication and measurement durations

The time taken for SDI-12 commands to be sent by the logger and for measurement results to be reported back by the WET150 forms a large part of the overall measurement time. This is due to the communication speed required by the SDI-12 specification.

Commands sent by loggers and responses sent by SDI-12 sensors are variable in length (and therefore transmission time). As an indication, a standard three-parameter W-E-T reading on a WET150 has the following typical durations:

- From start of SDI-12 measurement command to finish of SDI-12 data ready service request command (including active sensing and results computation): 360ms

- From start of SDI-12 data request command to finish of SDI-12 measurement data transmission: 240ms

SDI-12 communication interface

The WET150 is compliant with version 1.3 of the SDI-12 specification. In addition, the data port is protected from mis-wiring to Power or Ground.

Output High and Low data states (dependent on network loading)
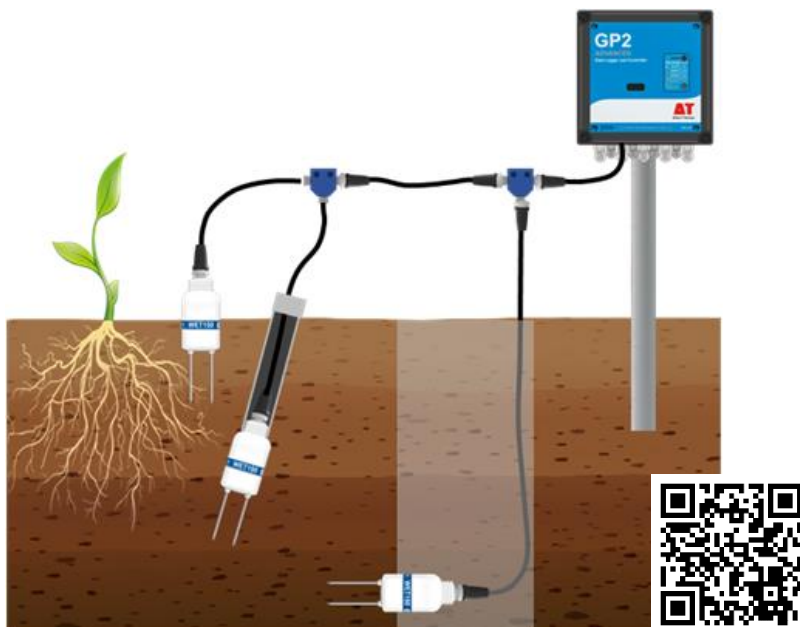
High: Typical 5V

Low: Typical 0V

Input High and Low data state requirements (relative to Ground voltage at the sensor)

High: Typical 5V (minimum 3.5V)

Low: Typical 0V (maximum 1.5V)

Installation in the Ground

A video showing how to install the WET150 in the ground can be found at:
https://youtu.be/ZRMUkiy-f3g or via the QR code.

Surface installation and spot measurements

Spot measurements

Consistent technique is critical for repeatable results when taking spot measurements. Varying how hard the sensor is inserted can be the dominant form of error in some soil types. Too much pressure will squeeze the soil/substrate, changing the bulk density and reading. Too little pressure and you may not push the hole length of the rods in and therefore be reading air.

- Clear away any stones. Pre-form holes in very hard soils before insertion.
- Push the WET150 into the soil, fully inserting the pins to ensure good soil contact.
- If you feel strong resistance when inserting the WET150 into soil, you may have hit a stone. Stop, and re-insert at a new location.

Note: With surface installation, air temperature and radiant heat on the sensor body can affect temperature readings. Partial or full burial of the WET150 will improve temperature accuracy, particularly where there is a large temperature difference between the air and the soil or substrate.

Installing at depth

■ Auger a 45mm diameter hole. ~10° to vertical is recommended.

■ Fit an extension tube to the WET150 – remember to pass the cable through the extension tube and fit the connector first.

■ Push the WET150 into the soil, fully inserting the pins to ensure good soil contact.

Alternatively

■ Dig a trench, and install horizontally.

■ When installing sensors into the side of the trench, we recommend making a shallow hole in the trench wall for the body of the sensor to sit in, rather than pushing the sensor pins directly into the wall and allowing the pins to support the sensor body. This will make the installation more secure and reduce the risk of sensors moving or becoming dislodged. This is explained in the video.

■ Note: Extension tubes are available for installing the WET150 in an augered hole.

Edge Effects

■ Keep the sensor pins away from the edge of plant plots if possible, to avoid the edge effect shown in the graph below.

WET150 Error close to wall of plant pot.

live pin nearest to pot wall
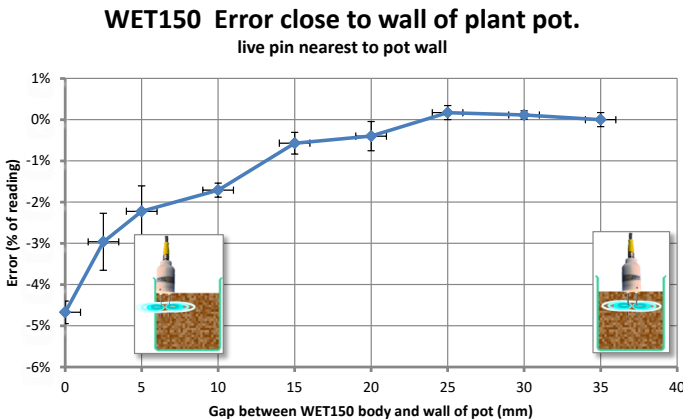
■ WET150 sensor may interact if they are placed too close together – they should be separated by at least 100mm.

SDI-12 commands

SDI-12 details are best handled by the GP2 logger controller itself within a logging program, as described in these previous sections. For system integrators and users of loggers from other companies see the WET150 SDI-12 Programmer's Guide.

This section gives a brief introduction to SDI-12 commands. The following command sequences are reviewed:

1. **Address Query** – find out the existing address of the single WET150 connected to the GP2
2. **Address Assign** – change the sensor's existing address to a new address
3. **Identify** – query the model, serial number and version of a sensor at a particular address
4. **Take a measurement**

The following examples explain what you need to type in the command entry box and how to interpret responses in the terminal window. The examples assume that the GP2's internal +12V supply (labelled +12V 0.5A) is being used for SDI-12 power. The GP2 automatically enables this supply when sending SDI-12 commands.

Address Query

The Address Query command is used to establish the SDI-12 address of a sensor. It is the only SDI-12 command which requires that just one sensor is connected at a time to a GP2 logger/controller. If more than one sensor is connected when the address query command is issued, all sensors will respond at the same time causing network corruption.

With just one WET150 connected to the GP2, type into the DeltaLINK transparent mode terminal window:

Type in command box	?	Press the <ENTER> key or click on the Send button
Terminal window shows	?!0	

The visible terminal window character string "?!0" can be broken down and explained as:

Commands from the GP2 logger/controller:

Character	Meaning
?	The SDI-12 command for "Address Query"
!	The SDI-12 end-of-command character (automatically added in transparent mode)

Reply from the WET150 sensor:

Character	Meaning
0	The response back from the WET150, in this example showing it is set to address 0 (zero). In real-world use the reported address could be different.

If the terminal window displays a sequence of ?!?!?!?!?!?!, press the <ENTER> key or click the SEND button again.

Address Assign

Having used the previous Address Query command to find out the address of the single connected WET150, the Address Assign command can be sent specifically for that addressed sensor to change its address. At this stage it is best if just one WET150 is connected to the GP2, particularly if you are configuring brand new sensors which may all be configured to respond on the same address.

In this example we will change the sensor address from 0 to d.

Using the DeltaLINK transparent mode terminal window:

Type in command box:	0Ad	Press the <ENTER> key or click on the Send button
Terminal window shows:	0Ad!d	

The visible terminal window character string "0Ad!d" can be broken down and explained as:

Commands from the GP2 logger/controller:

Character	Meaning
0	The SDI-12 address of the sensor you wish to communicate with
A	The SDI-12 command character for "Address Assign"
d	The new SDI-12 address should change to
!	The SDI-12 end-of-command character (automatically added in transparent mode)

Reply from the WET150 sensor:

Character	Meaning
d	The response back from the WET150, in this example confirming it is now set to address character **d**.

Identify

One further basic command may be useful to identify the model, version and serial numbers of a sensor. This command can be used with multiple sensors connected to the SDI-12 network as only the sensor matching the address in the command will respond. This command can also be used to identify if a specific SDI-12 address is already in use within the network.

In this example WET150 at address **d** will be queried.

Using the DeltaLINK transparent mode terminal window.

Type in command box:	`dI`	Press the <ENTER> key or click on the Send button
Terminal window shows:	`dI!d13Delta-T WET150v03 D1234567`	

The visible terminal window character string "`dI!d13Delta-T WET150v03 D1234567`" can be broken down and explained as:

Commands from the GP2 logger/controller:

Character	Meaning
`d`	The SDI-12 address of the sensor you wish to communicate with
`I`	The SDI-12 command character for "Identify"
`!`	The SDI-12 end-of-command character (automatically added in transparent mode)

Reply from the WET150 sensor:

Character	Meaning
`d`	The response back from the WET150, in this example confirming sensor at address character **d** is responding.
`13`	The sensor firmware conforms to SDI-12 specification version 1.3
`Delta-T`	Manufacturer
`WET150`	Product model name
`v03`	Sensor firmware version
`D1234567`	WET150 serial number

Take a measurement

The WET150 contains 9 pre-programmed measurement sets. The WET150 can use any of these measurement sets (shown in detail on the next page) as sequential or concurrent measurements, either with or without CRC error checking.

In summary, these measurement commands are:

Measurement type	Commands
Standard sequential	aM! and aM1! ... aM9!
Standard concurrent	aC! and aC1! ... aC9!
Sequential with CRC error checking	aMC! and aMC1! ... aMC9!
Concurrent with CRC error checking	aCC! and aCC1! ... aCC9!

where **a** is the address of the sensor.

All measurements sets other than **aM9!** can be customised. See the following sections for customisation details.

Note for those using non-Delta-T loggers/controllers: **Taking** a measurement and **reporting** a measurement are separate activities. When an **M!** or **C!** command is sent, the WET150 will take a measurement, but it will not report it until asked to with a **D0!** command. See the SDI-12 Programmer's Guide for more information.

Table of pre-configured measurements

The factory defaults for the ten pre-configured measurement sets are as follows (shown only using the M command for clarity, and using a sensor address of "a"):

Command	Response parameters	Units	Notes
aM!	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	mS.m^{-1}	
	T	°C	
aM1!	Water content	%vol	Using Mineral soil-type calibration
	EC_p (pore water EC)	mS.m^{-1}	Compensated to 25°C linearly at 2%/°C, using Mineral soil-type calibration
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	mS.m^{-1}	
aM2!	Water content	%vol	Using Organic soil-type calibration
	EC_p (pore water EC)	mS.m^{-1}	Compensated to 25°C linearly at 2%/°C, using Organic soil-type calibration
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	mS.m^{-1}	
aM3!	Water content	%vol	Using PeatMix soil-type calibration
	EC_p (pore water EC)	mS.m^{-1}	Compensated to 25°C linearly at 2%/°C, using PeatMix soil-type calibration
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	mS.m^{-1}	
aM4!	Water content	%vol	Using Coir soil-type calibration
	EC_p (pore water EC)	mS.m^{-1}	Compensated to 25°C linearly at 2%/°C, using Coir soil-type calibration
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	mS.m^{-1}	

aM5!	Water content	%vol	Using MinWool soil-type calibration
	EC_p (pore water EC)	$mS.m^{-1}$	Compensated to 25°C linearly at 2%/°C, using MinWool soil-type calibration
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	$mS.m^{-1}$	
aM6!			Blank
aM7!			Blank
aM8!			Blank
aM9!	ε_r (permittivity)	(none)	Fixed / Not customisable
	EC_b (bulk EC)	$mS.m^{-1}$	Fixed / Not customisable
	T	°C	Fixed / Not customisable

Customising measurement sets

Multi-parameter measurement sets M and M1 to M8 in the table above can be customised to better suit your application, particularly for use with third-party (non-Delta-T Devices) loggers and controllers.

Before modifying certain of the soil-specific parameters, the "soil type" (Mineral, Organic, etc.) for the measurement set must be set to "custom". As an example, the typical command sequence for modifying a soil parameter looks like this:

Command	Sensor reply	Notes
aXU1D?!	a -8.9	Command queries what the current ECp soil parameter is for measurement set M1 ("Mineral soil") for the sensor at address "a"; the sensor replies it is -8.9
aXU1B=Z!	a OK	Command tells the sensor that measurement set M1 is to be a "custom" soil type.
aXU1D=2.72!	a 2.72	Command then sets the ECp soil parameter for measurement set M1 to 2.72
aM1!	a\<values\>	Command requests a measurement using M1 (now using the custom soil parameter).

For information on how to make these measurement customisations see the WET150 SDI-12 Programmer's Guide.

Note about Pore EC (ECp) calculations:

The electrical conductivity of the water in the soil pores (ECp) is calculated by applying the Hilhorst equation. This is a very useful approximation that works well with the WET150 because the sensor measures permittivity and ECb in the same sample volume at the same frequency (100MHz).

However, the Hilhorst equation ceases to be a good approximation for ECp if the wrong soil type setting ("soil parameter") is used, and also when there is too little water present. It is therefore important to use an EC soil parameter that is a good match for your soil or substrate.
By default, the WET150 is shipped with generic parameters that match the generic parameters in Delta-T's WET2 sensor. We strongly recommend you review these settings. Best results will be obtained with a soil parameter customised to your specific application. If this is not feasible, the table at the back of this manual contains a list of generic parameters which give generally good performance for several common soils and substrates. Alternatively, the process described on page 65 can be used to determine a soil parameter, but this can give very variable results and is better treated as indicative only.

If you need more advice on this topic then please contact Delta-T for guidance.

If the WET150 is configured to calculate and output ECp, for example using pre-configured measurements M1 to M5, but the water content is too low to calculate a valid ECp, the WET150 will output error code -8020 (meaning "too dry") in the place of ECp value.

If using the generic built-in soil calibrations for converting permittivity to soil moisture content, the lower soil moisture limits for valid ECp calculations are:

Generic soil-type calibration	Lower limit soil moisture content for ECp calculation
Mineral	≈ 10 %vol
Organic	≈ 21 %vol
PeatMix	≈ 15 %vol
Coir	≈ 15 %vol
MinWool	≈ 8 %vol

Specifications

Volumetric Water Content (%vol)	
Accuracy	± 3%vol (with a calibration matching the soil / substrate)
Range	Accurate range: 5 to 100%vol, EC_b 0 to 500mS.m^{-1}. Full range: 0 to 100%vol
Permittivity (ε')	
Accuracy	± (3% of reading + 0.8 ε') 1 → 40 for ECp ≤ 800mS.m^{-1} ± 5% of reading 40 → 80 for ECp ≤ 500mS.m^{-1}
Range	Accurate range: 1 to 80, full range: 1 to 90
Bulk soil conductivity (EC_b)	
Accuracy	**± (6% of reading + 10 mS.m^{-1})**
Operating range	Accurate range: **0 to 1200mS.m^{-1}** Full range: 0 to 2000mS.m^{-1}
Temperature *(WET150 must be fully buried to accurately measure soil temperature)*	

Temperature		
Accuracy	**± 0.5 °C**	± 0.7 °C
Range	Accurate range: 0 to +40 °C	Full range: -20 to +60 °C

Operating specifications	
Interface	SDI-12 version 1.3
Max cable length[5]	>100 m see page 23
Power requirement	6 to 20 V, ~22 mA over 12 ms (with short 45mA peak) (see page 23)
Operating range	-20 to +60 °C (sensor does not detect ice)
Environmental	IP68[6]
Sample volume	55 x 70 mm diameter
Dimensions	143 x 40 mm diameter
Weight	77 gm (without cable)

---

[5] On an SDI-12 network
[6] Submerged in water to depth 4.5m for 24 hours

Pore Water EC (ECp) accuracy

The following graph indicates the range of pore water conductivity (ECp) that can be most accurately measured by the WET150 at different soil moisture levels:

Pore water conductivity accuracy
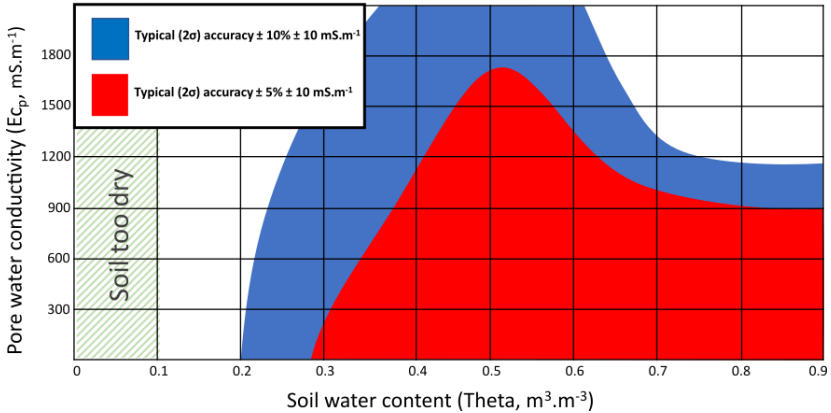
Notes:

[1] The WET150 has been carefully optimised to provide accurate readings in soils and substrates - readings taken in water or air may not meet the full specification.

[2] The ECp contour map is based on measurements from 30 sensors at 20°C in NPL* traceable media. Calculated ECp readings are derived from the Hilhorst equation, using the generalised "mineral" soil calibration and the default soil parameter = 4.1

* NPL is the UK's National Physics Laboratory, developing and maintaining the national primary measurement standards.

Error Codes

Error code -8020 may be reported in very dry soils in place of the expected Pore EC value. *This is not a sensor fault*.

All other error codes indicate a possible sensor fault condition. Please contact Delta-T devices support for assistance.

Configuration

The WET150 has several user-configurable parameters which can be used to adjust its performance in different soils and substrates. Adjusting these can have a significant effect on the accuracy of your sensor, but before changing them it is useful to understand how they work and what they operate on. Below is a brief introduction – for more information see the section "Technical Reference" (page 44).

Please note that, when using the WET150 with a GP2 or WET150 Meter, the calculations of EC_p and water content are not done by the sensor but by the GP2/Meter handheld unit. In this case, any customisation needs to be done on the GP2/Meter, and the parameters stored in the WET150 sensor do not need to be modified.

By default, the WET150 is shipped with generic parameters that match the generic parameters in Delta-T's WET2 sensor. We strongly recommend you review these settings. The parameters available to adjust are as follows:
1. To adjust water content calculation:
    a. a_0
    b. a_1
2. To adjust EC_p calculation:
    a. Soil parameter (sometimes called ε'_0 or $\varepsilon'_{\sigma_b=0}$)
    b. EC_p dry limit.

The function of these parameters is discussed in the Technical Reference section (page 44).

Best results will be obtained with parameters customised to your specific application. If this is not feasible, the table at the back of this manual contains a list of generic parameters which give generally good performance for several common soils and substrates.

The parameters stored in the sensor can be adjusted either before or after installation and connection to an SDI-12 network, and the steps required to modify these parameters vary slightly depending on what equipment the sensor is connected to. The rest of this manual will guide you through how to connect your sensor and communicate with it.

How it works

Sensing soils and substrates

The WET150's operation is based around the concept of sensing electrical impedance around its pins. A short burst of a 100MHz signal is applied to the pins forming an electromagnetic field around them. The electrical loading that the soil or substrate places upon the pins is digitally sampled by amplitude and phase detector circuits giving simultaneous measurements of real and imaginary impedance. The processor in the WET150 then calculates the dielectric properties of the soil or substrate from these impedance measurements to give:

Real permittivity	ε'	(unitless)
Bulk electrical conductivity	EC_b	(default units mS.m^{-1})

Along with temperature (T, default units °C), these three measurements form the native WET150 outputs which can be logged directly or used in further calculations.

It is possible to calculate the water content of any soil or substrate from its permittivity value, provided that certain composition properties of the soil or substrate are known.

Permittivity and soil composition

Soils are typically composed of several materials mixed together in varying quantities, examples include sand, organic particles, water, stones and air. Electromagnetic fields interact differently with each of these individual materials.

In physics, comparison measurements can be made between how an electromagnetic field interacts with a material and how the same electromagnetic field interacts with a perfect vacuum. The response in a perfect vacuum is taken as the reference and is given the relative permittivity value of 1. All other materials have a measured relative permittivity value compared with that of a vacuum.

Some examples of approximate relative permittivity values at 20°C are:

Material	Relative permittivity
Perfect vacuum	1
Air	1.0006
Dry wood	2 – 6
Dry silica sand	2.5 – 3.5
Quartz	4.5
Water	80.4

When these and other materials are combined together to form a soil or substrate, the WET150 detects the overall permittivity which is formed from their individual permittivity contributions, depending upon their relative quantity in the mix.
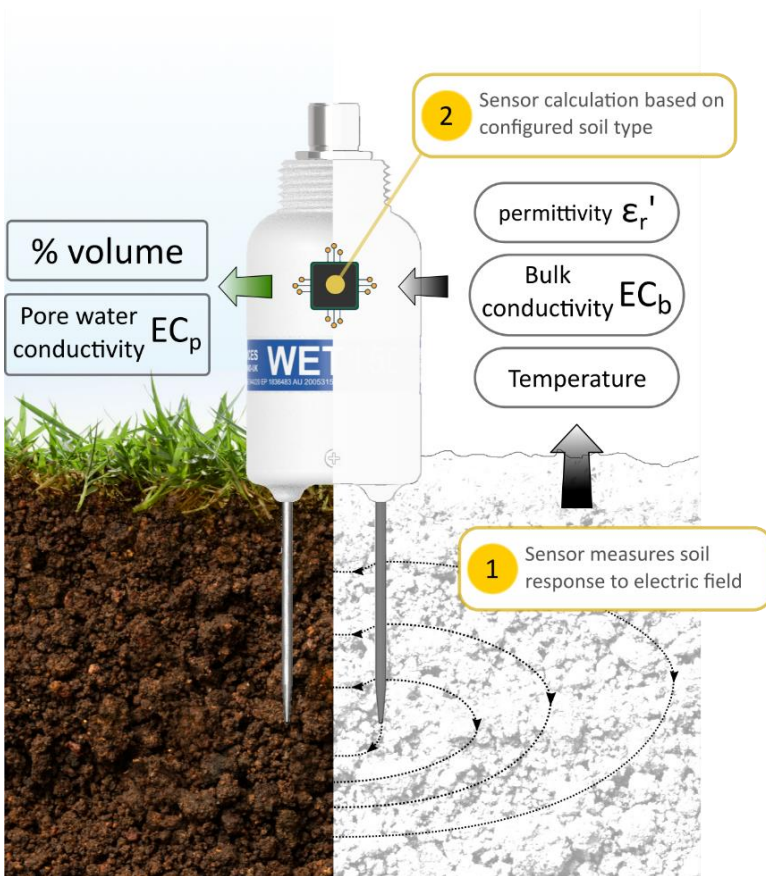
Converting permittivity to water content

The relationship between soil permittivity (ε') and its equivalent water content (θ), depends upon the mix proportions of its constituent materials (sand, organic matter, water, air, etc). This relationship between soil permittivity and water content is also non-linear.

However, for any given soil it can generally be assumed that the permittivity contribution from the soil particles is constant, so the permittivity measured by the WET150 is only affected by changes in water content. Also, by using the square-root of permittivity (called the *refractive index*), it is possible to further simplify the

relationship with water content as:

$$\sqrt{\mathcal{E}'} = a_0 + (a_1 \cdot \theta)$$

where the coefficients a_0 and a_1 conveniently parameterise the dielectric properties of the soil.
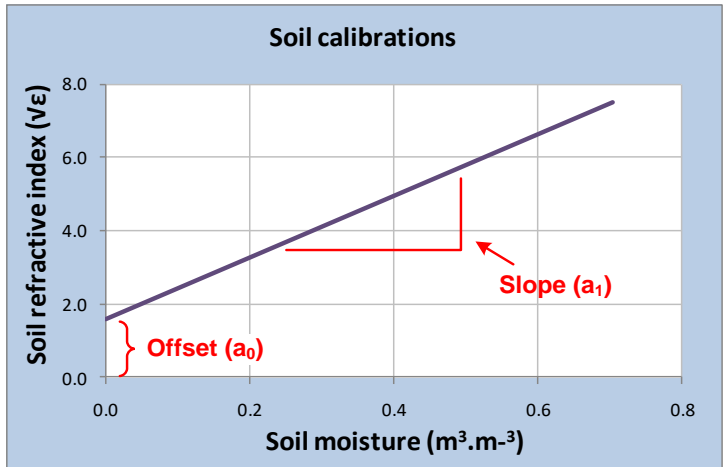
Note that:

$$a_0 = \sqrt{\mathcal{E}'_{dry\_soil}} \text{ is usually between 1.3 and 2.3}$$

a_1 corresponds approximately to $\sqrt{\mathcal{E}'_{water}} - 1$ and usually takes a value about 8.0.

Real soil a_0 and a_1 values can vary significantly from these guidelines when they are affected by other factors – in particular, bound water in clay may result in higher values of a_1.

Generic soil calibrations

Most soils and substrates can be characterised simply by choosing one of the generic soil types listed in Appendix 2 for measurements of water content. The mineral generic soil type is for soils which are predominantly made of sand, silt and clay. The organic generic soil type is for soils with a high organic matter content. See also Definitions on page 52
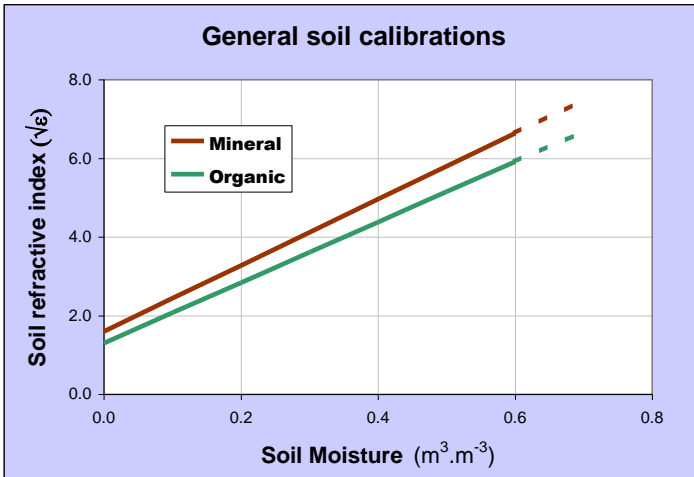
In DeltaLINK, the soil type for a WET150 logging program can be selected from a drop-down in the properties panel on the right of the program editor window, under the calculation section. This auto-populates the a_0 and a_1 values for the water content (theta) calculation.

Note: As the properties panel is context sensitive, the 'Theta' measurement must first be selected in the overview panel on the left of the program editor window.

The WET150 is also able to directly compute and output soil water content for the generic soil types (on page 42). The pre-configured WET150 measurement sets and SDI-12 commands assigned to these generic soil types are given in the tables following page 32. See the WET150 SDI-12 Programmer's Guide for more information on outputting water content measurements directly from the WET150.
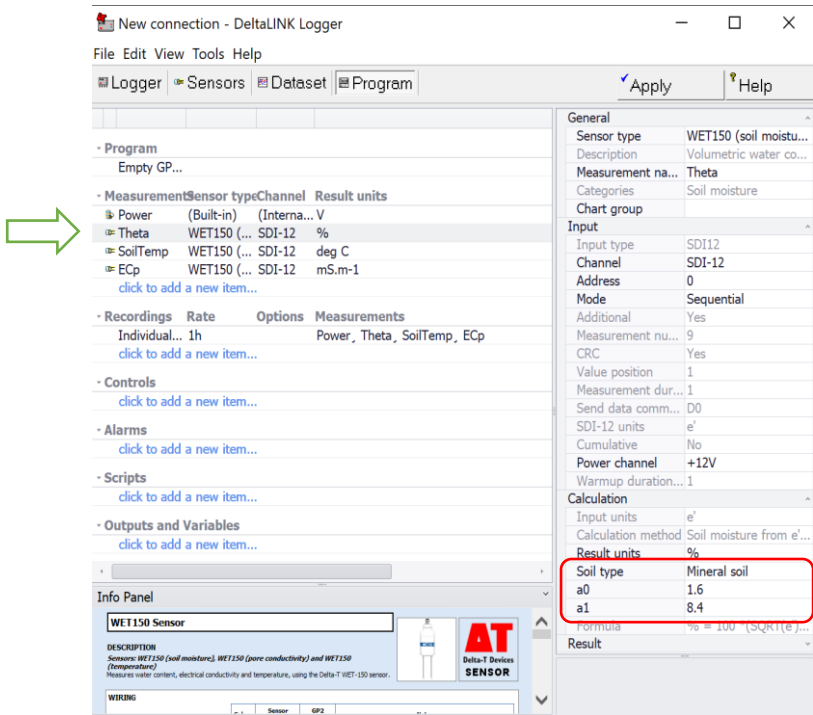
Soil-specific calibrations

Instead of adopting the generic soil calibrations, you may wish to determine specific soil calibration values of a0 and a1 for your soil. Soil-specific calibrations can significantly improve the accuracy of individual readings - but make less of an improvement to readings where installation and sampling errors are high. This procedure is fairly straightforward if you have access to standard laboratory equipment and is described in detail in the Appendix on page 59.

In DeltaLINK, a WET150 logging program using custom a_0 and a_1 values from a soil-specific calibration can be entered in the properties panel on the right of the program editor window, under the calculation section. These values will then be used for the water content (theta) calculation.
Note: As the properties panel is context sensitive, the 'Theta' measurement must first be selected in the overview panel on the left of the program editor window.

The WET150 is also able to directly compute and output soil water content using custom a_0 and a_1 values from a soil-specific calibration.

Technical Reference

Dielectric properties

When an electric field passes through a material (such as soil) some of the energy in the field is transmitted (unchanged), some is reflected, some is stored and some is absorbed and converted into heat.

The extent to which each of these occurs within a particular material is determined by its *dielectric properties*. These are quantified by a parameter called the relative electrical *permittivity* (ε) of a material which characterises its response to the polarising effect of an applied electric field.

It is usually represented as a complex number,

$$\varepsilon = \varepsilon' - j\varepsilon'' \qquad\qquad\qquad \text{[1.]}$$

where the real part of the permittivity, ε', represents the energy stored, and the imaginary component, ε'', represents the total energy absorption or loss. Both values are frequency and temperature dependent.

For a static electric field the real part of the permittivity, ε', is often referred to as the dielectric constant.

The energy losses include dielectric loss, ε''_d, and loss by ionic conduction:

$$\varepsilon'' = \varepsilon''_d + \frac{EC_i}{\omega\varepsilon_0} \qquad\qquad\qquad \text{[2.]}$$

where EC_i is the specific ionic conductivity of the material and ω is the radian frequency in rad s^{-1}. The frequency in Hz of the applied electric field is $f = \omega/2\pi$.

The permittivity for free space is ε_0 = 8.854 10^{-12} F m^{-1}.

> *Note: in the remainder of this theory we've used the symbol σ instead of EC for the electrical conductivity, in order to simplify the appearance of the equations.*

Measuring Soil Moisture

Whalley (1993), White, Knight, Zeggelin and Topp 1994) have shown that there is a simple linear relationship between the complex refractive index (which is equivalent to $\sqrt{\varepsilon}$), and volumetric water content, θ, of the form:

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta$$

[3.]

This equation appears to work very well for most non-magnetic soils and artificial growing media over a range of frequencies between ~1MHz and ~10GHz.

The following graph shows composite data for a number of different agricultural soils
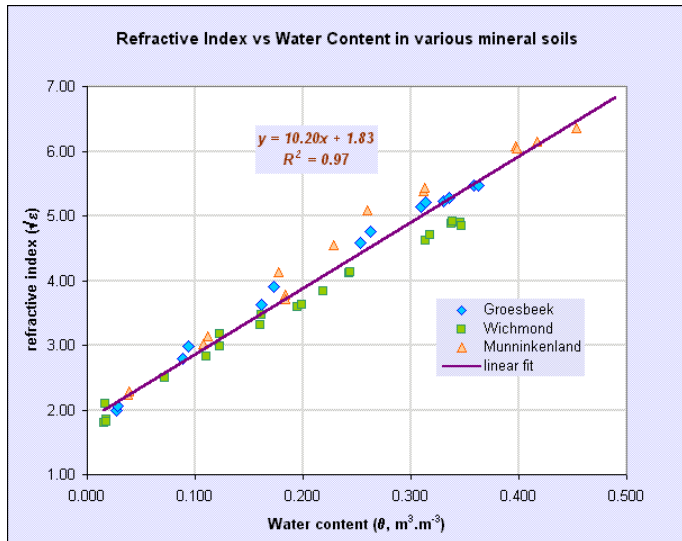
You can see from this graph that the accuracy of the water content measurements would be improved by using a different calibration for each soil. However, the improvement would be small (typically 2 or 3%), so a generalised "mineral" calibration is appropriate for a good range of agricultural soils.

Warning: This is not the case with clay soils, and a soil-specific calibration may improve the accuracy by >10%. This is also true of "organic" soils because that label covers a huge range of soil types.

Pore water conductivity

The electrical conductivity of the bulk soil, σ_b, is a function of both soil water content, θ, and the pore water conductivity σ_p.

This is very similar to the relationship that has been found between the electrical permittivity of the bulk soil, ε_b, the permittivity of the pore water, ε_p, and θ (e.g. Nyfors and Vainikainen, 1989).

Malicki *et al*. (1994) found a high degree of linear correlation between values of σ_b and ε_b for a broad range of soil types.

The following discussion proposes a theoretical basis for the relationship between σ_b and ε_b, and explains how this is used within the WET150 Sensor to derive readings of pore water conductivity.

Bulk Soil Conductivity v. Pore Water Conductivity

Consider the water that can be extracted from the pores of the soil matrix. The permittivity and conductivity of the pore water will be denoted by the subscript p. The imaginary part of the complex permittivity of the pore water is ε''_p. In soil science it is more practical to use the conductivity of the pore water, σ_p, which can be defined as:

$$\sigma_p = \omega\varepsilon_0\varepsilon''_p = \omega\varepsilon_0\left(\varepsilon''_{dp} + \frac{\sigma_{ip}}{\omega\varepsilon_0}\right) \qquad [4.]$$

where σ_{ip} represents the ionic conductivity of the extracted pore water. Dielectric losses are frequency dependent and have a maximum at the relaxation frequency. The relaxation frequency of water is 17 GHz at 20°C (Kaatze and Uhlendorf, 1978). The operating frequency of the WET150 Sensor is 100MHz, and at that frequency ε''_{dp} is negligible, so Eq. [5] can be reduced to:

$$\sigma_p = \sigma_{ip} \qquad [5.]$$

Usually σ_p is referred to as the *EC* (Electrical Conductivity) of the pore water. Ionic conduction is a function of temperature. In the case of a NaCl-water mixture, the conductivity increases by ~2.1 % per °C. The values quoted for σ_p are often corrected for temperature dependence to a temperature of 20°C (or sometimes to 25°C). This temperature correction depends on the ionic composition of the solution, and it can be applied automatically by the WET150 Sensor.

The complex permittivity of the pore water, ε_p, is equal to that of pure water. The real part of the complex permittivity of the pore water ε'_p = 80.3 at 20°C, with a temperature coefficient of about -0.37 per °C (Kaatze and Uhlendorf, 1981).

By analogy with Eq. [4] we can write the following approximation for ε_p:

$$\varepsilon_p \approx \varepsilon'_p - j\frac{\sigma_p}{\omega\varepsilon_0} \qquad [6.]$$

The permittivity and conductivity of the bulk soil will be denoted by the subscript b. The complex permittivity of the bulk soil, ε_b, is proportional to both ε_p and a function of θ, $g(\theta)$. For dry soil there is no water to facilitate ionic conduction, so the conductivity of the bulk soil $\sigma_b \approx 0$.

Dry soil material is still polarisable,

so $\varepsilon_{\sigma_b=0} \neq 0$ and $\varepsilon_{\sigma_b=0}$ appear as an offset to ε_b.

By assuming that $g(\theta)$ takes into account the proportionality constant, it is reasonable to postulate the following form for the complex permittivity of the bulk soil:

$$\varepsilon_b = \varepsilon_{\sigma_b=0} + \varepsilon_p g(\theta) \qquad [7.]$$

Note that $\varepsilon_{\sigma_b=0}$ is a complex value and includes dielectric and ionic loss. However since $\sigma_b = 0$, we may approximate $\varepsilon_{\sigma_b=0}$ by its real part $\varepsilon'_{\sigma_b=0}$. With this and Eq. [6] substituted in Eq. [7], ε_b can be written as:

$$\varepsilon_b = \varepsilon'_{\sigma_b=0} + \varepsilon'_p g(\theta) - j \frac{\sigma_p}{\omega \varepsilon_0} g(\theta) \qquad [8.]$$

An electrical model for a dielectric material such as soil between two electrodes is a lossy capacitor. We can calculate the admittance, Y, of this soil-filled capacitor. The admittance is the inverse of impedance, Z, and is a complex quantity which is proportional to the permittivity ε_b of the bulk soil, and can be defined by:

$$Y = j\omega\varepsilon_0\varepsilon_b\kappa \qquad [9.]$$

where κ is a geometry factor which is determined by the distance between the electrodes and their areas in contact with the soil. Note that contact problems of the electrodes with the soil will be reflected in κ.

The equivalent circuit for such a lossy capacitor is a loss-free capacitor, C, with a conductor, G, in parallel. C represents the energy storage capability of the soil and is related to ε'_b.

G represents the energy loss and is related to σ_b. Y may be written in terms of C and G as:

$$Y = G + j\omega C \qquad [10.]$$

From Eq. [9] and Eq. [10] and with Eq. [4] to Eq. [8] in mind, the real and imaginary parts of Y can be found:

$$G = \sigma_p g(\theta)\kappa \qquad [11.]$$

and

$$C = \varepsilon_0\left(\varepsilon'_{\sigma_b=0} + \varepsilon'_p g(\theta)\right)\kappa \qquad [12.]$$

In terms of the measurable bulk quantities σ_b and ε'_b:

$$\sigma_b = \sigma_p g(\theta) \qquad\qquad [13.]$$

and

$$\varepsilon'_b = \varepsilon'_{\sigma_b=0} + \varepsilon'_p g(\theta) \qquad\qquad [14.]$$

From Eq. [13] and [14] the ionic conductivity of the pore water can be written as:

$$\sigma_p = \frac{\varepsilon'_p \sigma_b}{(\varepsilon'_b - \varepsilon'_{\sigma_b=0})} \qquad\qquad [15.]$$

The model of Eq. [15] describes the relationship between σ_p of the pore water (the water that can be extracted from the soil) and the values ε'_b and σ_b as measured in the bulk soil using a dielectric sensor. The offset $\varepsilon'_{\sigma_b=0}$ can be calculated from the ε'_b and σ_b values measured at two arbitrary free water content values.
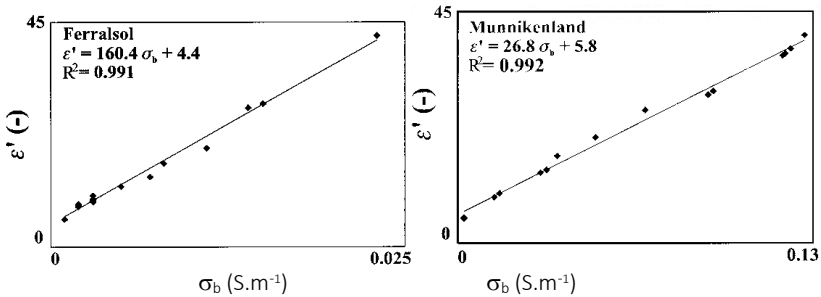
Figure 1 - Examples of the relationship between ε'_b and σ_b, showing the offset $\varepsilon'_{\sigma_b=0}$ for two different soils.

The relationship between the bulk soil parameters ε'_b and σ_b and the corresponding pore water parameters ε'_p and σ_p is different when the water present is bound to the soil matrix rather than free water. The model of Eq. [15] cannot be used for the conductivity due to ions moving through the lattice of ionic crystals in a dry or almost dry soil - the model is only valid for the free water in the matrix.

Thus $\varepsilon'_{\sigma_b=0}$ is not the value for ε'_b if $\theta = 0$.

For sand the free water content corresponds to $\theta > 0.01$ but for clay it can be $\theta > 0.12$ (Dirksen and Dasberg, 1993). As a rule of thumb the model applies for most normal soils and other substrates used for growing, such as Rockwool, if $\theta > 0.10$.

EC_p Model Limitations and Practical Implications

Considering equation 15 above, it should be clear that this equation will produce anomalous results as $\varepsilon'_b \rightarrow \varepsilon'_{\sigma_b=0}$, where the results will tend to +/- ∞. The effect of this is that there is a transition from accurate ECp readings to near-infinite anomalous readings. The shape of this transition zone is dependent on the soil's physical and chemical characteristics, and how well the soil parameter is matched to the soil/substrate. This means that the soil parameter $\varepsilon'_{\sigma_b=0}$ has two simultaneous effects: it changes the overall accuracy of the ECp output at general moisture levels, and it also affects the shape of the transition approaching the asymptotic limit[7]. Ideally, a soil parameter would be chosen to give good accuracy across most moisture levels, and while it cannot be avoided, it would also minimise the transition from accurate readings to near-infinite output. In the WET150, the "too dry" threshold can then be adjusted to prevent the anomalous readings being reported. A poorly matched soil parameter, by comparison, will give an offset ECp, and a more gradual transition to infinite readings at low moisture content, making the "too dry" threshold less effective.

Illustration of WET150 sensor Ecp readings with a well-matched soil parameter

1 — Erroneous ECp output not reported because it occurs below "too dry" limit.

2 — ECp accurately reported

True ECp

"Too dry" limit (approx. 16% in this example)

Sensor ECp output

Gravimetrically derived Volumetric Water Content
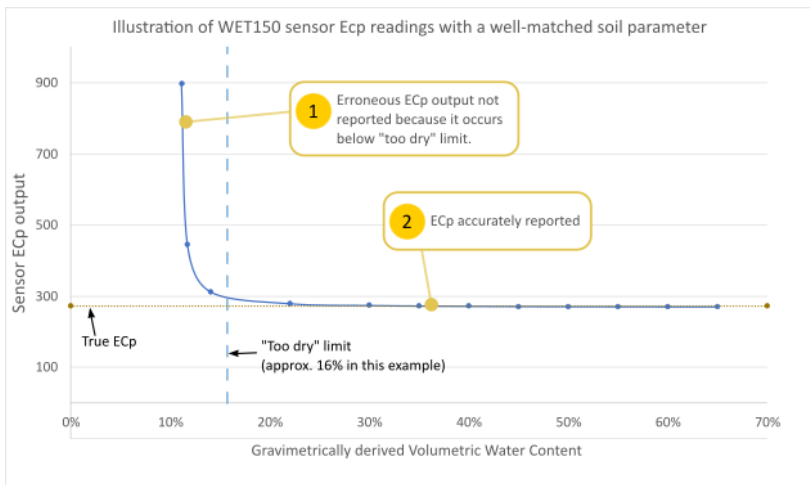
Figure 2 - illustration of sensor output with a well-matched soil parameter. Note that this illustration shows readings tending to positive infinity, but a negative infinity asymptote is also possible

The suitability of a soil parameter can depend on many factors. Not only the soil type, but also its age, density, chemical composition, and many other factors can affect what soil parameter is optimal. It is also important to ensure that the soil parameter is chosen based on the expected operating range i.e. what moisture contents and salinities are expected to be experienced.

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[7] A negative soil parameter avoids this problem but may be a poor choice for overall accuracy.

Given the wide variety of soils and substrates in terms of their composition and properties, and the simplicity of the model, these two effects (viz. the overall accuracy and the size of the transition zone) are affected by different factors, and in reality it is often not possible to optimize for both.
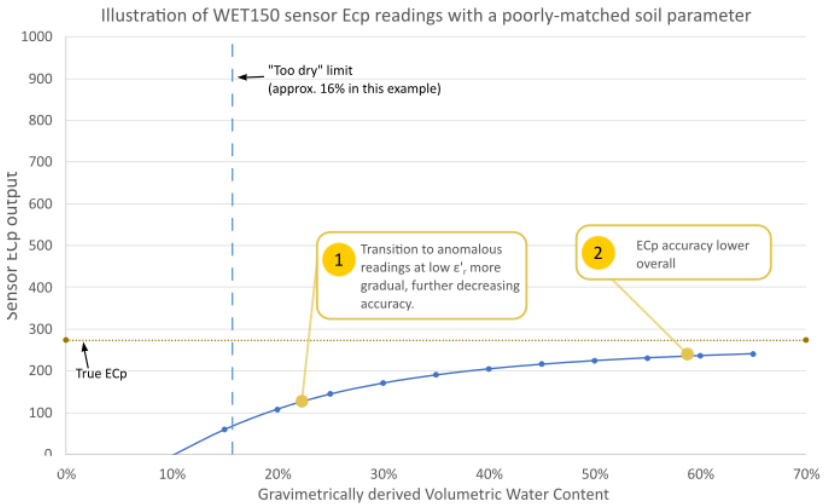
Figure 3 - Illustration of how sensor ECp output is affected by a poorly-matched soil parameter. Note that although this illustration tends to negative infinity, either positive or negative infinity asymptotes are possible

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Definitions

Volumetric Soil Moisture Content

$$\theta_V = \frac{V_W}{V_S}$$

where

V_w is the volume of water contained in the sample

V_s is the total volume of the soil sample.

The preferred units for this ratio are $m^3.m^{-3}$, though %vol is frequently used.

Soil Moisture Content varies from approx. 0.04 $m^3.m^{-3}$ for sandy soils at the permanent wilting point, through approx. 0.4 $m^3.m^{-3}$ for clay soils at their field capacity, up to values as high as 0.85 $m^3.m^{-3}$ in saturated peat soils.

Gravimetric Soil Moisture Content

$$\theta_G = \frac{M_W}{M_S} \, g.g^{-1}$$

where

M_w is the mass of water in the sample, and

M_S is the total mass of the dry sample.

To convert from volumetric to gravimetric water content, use the equation

$$\theta_G = \theta_V \times \frac{\rho_W}{\rho_S}$$

where

ρ_W is the density of water (= 1g.cm^{-3}), and

ρ_S is the bulk density of the sample $\frac{M_S}{V_S}$.

Organic and Mineral soil definitions:

The general calibrations have been optimised to cover a wide range of soil types, based on the following definitions:

Soil type	optimised around organic content:	use for organic contents:	bulk density range: ($g.cm^{-3}$)	use for bulk densities: ($g.cm^{-3}$)
Mineral	~ 1 %C*	< 7 %C	1.25 - 1.5	> 1.0
Organic	~ 40 %C	> 7 %C	0.2 - 0.7	< 1.0

* Note: %C denotes "percentage Carbon" and is a measure of organic content

Salinity

The preferred SI units for ionic conductivity are $mS.m^{-1}$ (where S is Siemens, the unit of electric conductance. Dimensionally it is equivalent to the inverse of resistance i.e. Ohm^{-1}).

The following conversions apply:

$1\ mS.m^{-1}$ $= 0.01\ dS.m^{-1}$

$= 0.01\ mS.cm^{-1}$

$= 10\ \mu S.cm^{-1}$

Soil salinity can be classified using the following descriptive categories:

Classification of salinity
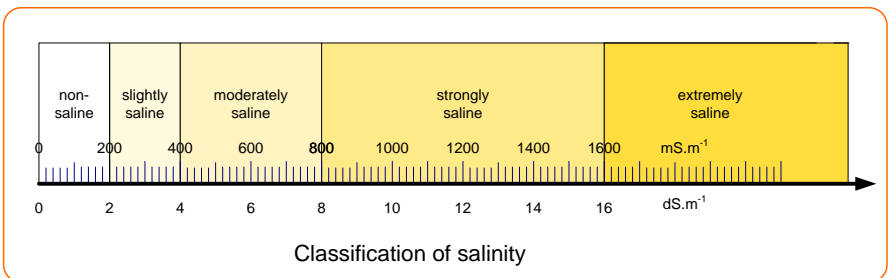
Electrical Conductivity

The Electrical Conductivity (EC) of a material is a measure of its ability to carry an electrical current. It is an "intrinsic" property of the material into which the electrodes are inserted, i.e. a property which is defined at a point and does not depend on how much material is present (q.v. density)

Electrical Conductance (G)

A measure of the current carrying ability of an "extensive" sample of material, and depends on the particular measurement set-up, particularly the length (L) and cross-sectional area (A) of the measurement cell.

Conductivity and conductance are related by the formula

$$EC = G.\frac{L}{A}$$

$$= G.C \quad \text{(S.m-1), where C is the Cell Constant.}$$

Electrical Conductivity is measured in Units of Siemens per meter (S.m^{-1}). We have used mS.m^{-1} throughout this manual because it is an SI preferred unit.

The following conversions apply:

$$1 \text{ mS.m}^{-1} = 0.01 \text{ mS.cm}^{-1} = 10 \text{ μS.cm}^{-1}$$

Pore Water Conductivity (EC$_p$ or σ$_p$)

The *electrical* conductivity of the water within the soil pores. It is determined by the concentration of different ions within the pore water, and by the temperature.

Bulk Electrical Conductivity (EC$_b$ or σ$_b$)

The total *electrical* conductivity of the soil, and is a function of *pore water conductivity*, soil particle conductivity, *soil moisture content*, and soil composition.

Permittivity (ε)

The *Permittivity* of a material characterises its response to the polarising effect of an applied electric field. It is usually represented as a complex number, $\varepsilon = \varepsilon' - j\varepsilon''$, where the real part of the permittivity, ε', represents the energy stored, and the imaginary

component, ε'', represents the total energy absorption or loss. Both values are frequency and temperature dependent.

Permittivity is commonly used as a means of measuring water content, because the real permittivity of water is ~80 at 100 MHz, 20°C, whereas the permittivity of most soil particles is typically in the range 3 to 8.

Dielectric

Best used as a descriptive term, e.g. "*dielectric* materials" usually refers to insulating materials with a high relative permittivity.

Dielectric constant

Sometimes used interchangeably for *permittivity* but may be more rigorously defined as the real part of the *permittivity* in a static electric field.

Saturation

The moisture content at which all the air within the pores has been replaced by water. It's not a stable situation because the water will immediately start to drain through. It's a property of soil type only.

Field Water Capacity (or Field Capacity)

The moisture content obtained when a saturated soil has been allowed to drain (sometimes taken as 2 days later, sometimes when drainage has become "negligible").

It's a property of soil type only, and typically varies between 0.1 $m^3.m^{-3}$ for sandy soils up to about 0.40$m^3.m^{-3}$ for clay soils.

Wilting Point

The moisture content at which a particular crop is unable to extract any more water. Conventionally this is taken to correspond to a matric potential of −1500 kPa, but it's really much more variable than that suggests. It's a property of soil type and crop type, and can vary between about 0.04 $m^3.m^{-3}$ for sandy soils to 0.22 $m^3.m^{-3}$ for clay soils.
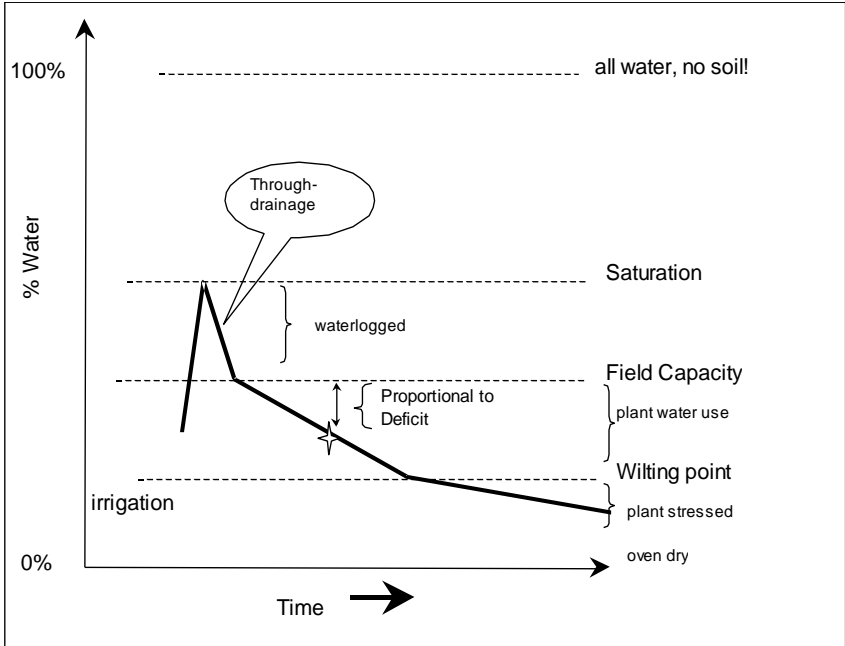
Dry

Zero moisture content.

Available Water Capacity

The difference between Field Capacity and Wilting Point.

Water Deficit

The amount of irrigation water or rainfall (mm) that has to be added to a soil profile in order to bring it back up to field capacity.

Technical Support

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Please refer to our Terms and Conditions via the link at the foot of our home page at www.delta-t.co.uk

Extended Warranty

All Delta-T Devices products have a two-year (24 month) warranty as standard, but the WET150, ML3, SM150T and SM300 soil moisture sensors benefit from a 5-year warranty (60 months from date of delivery). Simply register the product(s) with us via and we will add 3 more years to the standard warranty, extending it to the full 5 years duration. To qualify, products must be registered within 12 weeks of delivery.

All WET150s, SM150s, SM150Ts, SM300s and ML3s sold since 1 January 2016 are eligible.

Visit the Support Section of our website www.delta-t.co.uk to register your sensor for an extended 5 year warranty

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Technical Support is available on Delta-T products and systems. Your initial enquiry will be acknowledged immediately with a reference number. Make sure to quote the reference number subsequently so that we can easily trace any earlier correspondence.

In your enquiry, always quote instrument serial numbers, software version numbers, and the approximate date and source of purchase where these are relevant.

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Appendix 1

Soil-specific Calibration

This note describes two techniques for generating soil-specific calibrations:

- Laboratory calibration for substrates* and non-clay soils
- Laboratory calibration for clay soils

* We use the term substrate to refer to any artificial growing medium.

Underlying principle

Soil moisture content (θ) is proportional to the refractive index of the soil (√ε) as measured by the WET150 (see Technical Reference on page 44).
The goal of calibration is to generate two coefficients (a0, a1) which can be used in a linear equation to convert probe readings into soil moisture:
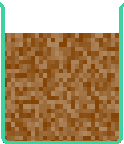
$$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$
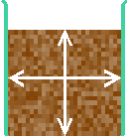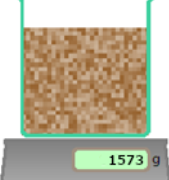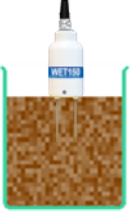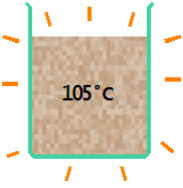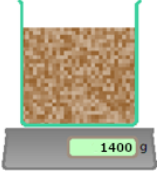
Laboratory calibration for non-clay soils

This is the easiest technique, but it's not suitable for soils that shrink or become very hard when dry.
Equipment you will need:

- WET150 and WET150 Meter with the Soil type set to "RAW".

- Soil corer (if doing a calibration for a cohesive soil rather than sand or a substrate)

- Heat-resistant beaker (≥ 1.0 litre)

- Weighing balance (accurate to < 1g)

- Temperature controlled oven (for mineral soils or substrates)

Process	Notes and example
	Collect a damp sample of the soil or substrate. This sample needs to be unchanged from its in-situ density, to be ~ 1.0 litre, to have the correct dimensions to fit the beaker, and to be generally uniform in water content. For cohesive soils this is most easily done with a soil-corer.

	Sandy soils can be repacked into the beaker, but if the sample is quite damp you should take the subsequent measurements quickly, as the water may begin to drain to the bottom of the beaker. Compressible soils and composts may require measurement of the in-situ density and then need to be carefully reconstituted at that density within the beaker.
	Measure the volume occupied by the sample. $L_s = 960.0ml$
1573 g	Weigh the sample, including the beaker. $W_w = 1573g$
WET150	Insert WET150 into the sample, press [Read] on the meter and record the permittivity reading (ε'). $\varepsilon_w = 9.06$, I.e. $\sqrt{\varepsilon_w} = 3.01$
105°C	Dry the sample thoroughly. With mineral soils this is usually achieved by keeping it in the oven at 105°C for several hours or days (the time required depends on the sample size and porosity). For organic soils / composts it's advisable to dry the sample at a lower temperature to avoid driving off volatile factions.
1400 g	Weigh the dry sample in the beaker. $W_0 = 1400g$

	Re-insert the WET150 into the dry sample and again record the permittivity reading. ε_0 = 2.56, I.e. $\sqrt{\varepsilon_0}$ = 1.60
Calculate a_0	Since the water content of the dry soil, θ_0 = 0, this gives a_0 directly: $\sqrt{\varepsilon_0} = a_0 = 1.60$
Calculate θ_w	The water content of the wet soil, θ_w, can be calculated from the weight of water lost during drying, $(W_w - W_0)$ and its volume, L_s: $$\theta_w = (W_w - W_0)/L_s = (1573 - 1400)/960 = 0.180$$ $$\theta_w = 0.180$$
Calculate a_1	$$a_1 = \left(\sqrt{\varepsilon_w} - \sqrt{\varepsilon_0}\right)/(\theta_w - \theta_0)$$ $$= (3.01 - 1.60)/(0.173 - 0) = 7.82$$
Result	a_0 = 1.60 a_1 = 7.82

This soil is now calibrated - you can now use these two numbers in place of the default calibrations to convert WET150 readings into volumetric water content ϑ using:

$$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$

See the WET150 SDI-12 Programmer's Guide for details on how to configure the WET150 to output soil moisture readings directly using custom calibrations. To modify a_0 and a_1 values in the WET150 Meter, see the WET150 Kit Quick Start Guide.
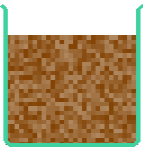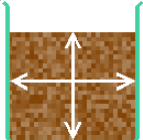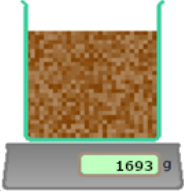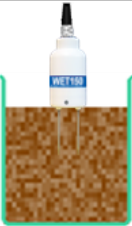
See also Underlying principle on page 59.
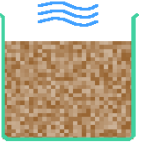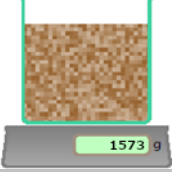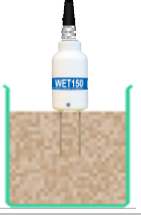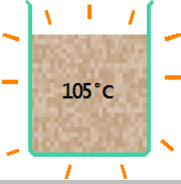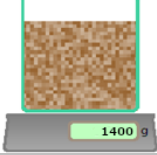
Laboratory calibration for clay soils

This technique is adapted to avoid the difficulty of inserting the WET150 into completely dry clay soil. It requires taking measurements at 2 significantly different, but still damp, moisture levels.

Equipment you will need:

- WET150 and WET150 Meter with the Soil type set to "RAW".
- Soil corer
- Heat-resistant beaker ($\geq$ 1.0 litre)
- Weighing balance (accurate to < 1g)
- Temperature controlled oven

Process	Notes and example
	Collect a _wet_ sample of the clay soil: 25 to 30% water content would be ideal. This sample needs to be unchanged from its in-situ density, to be ~1.0 litre, to have the correct dimensions to fit the beaker, and to be generally uniform in water content. This is most easily done with soil-corer.
	Measure the volume occupied by the sample. L_s = 960ml
	Weigh the wet sample, including the beaker. W_w = 1693g
	Insert WET150 into the sample, press [Read] on the meter and record the permittivity reading (ε'). ε_w = 15.90, I.e. $\sqrt{\varepsilon_w}$ = 3.99

	Dry the sample until still moist, ~15% water content. Gentle warming can be used to accelerate the process, but take care not to over-dry in places, and allow time for the water content to equilibrate throughout the sample before taking a reading.
	Reweigh. $W_m = 1573g$
	Re-insert the WET150 into the moist sample and again record the permittivity reading. $\varepsilon_0 = 9.06$, I.e. $\sqrt{\varepsilon_0} = 3.01$
	Dry the sample thoroughly. With clay soils this is usually achieved by keeping it in the oven at 105°C for several hours or days (the time required depends on the sample size and porosity).
	Weigh the dry sample in the beaker. $W_0 = 1400g$
Calculate θ_w	The water content of the wet soil, θ_w, can be calculated from the weight of water lost during the full drying process, $(W_w - W_0)$ and its volume, L_s: $$\theta_w = (W_w - W_0)/L_s = (1693 - 1400)/960 = 0.305$$ $\theta_w = 0.305$
Calculate θ_m	The water content of the moist soil, θ_m, can be calculated from the weight of water lost, $(W_m - W_0)$ and its volume, L_s: $$\theta_m = (W_m - W_0)/L_s = (1573 - 1400)/960 = 0.180$$ $\theta_m = 0.180$
Calculate a_1	Then $a_1 = \dfrac{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_m}}{\theta_w - \theta_m} = \dfrac{3.99 - 3.01}{0.305 - 0.180} = 7.82$

	$a_1 = 7.82$
Calculate a_0	and $\boldsymbol{a_0 = \sqrt{\varepsilon_w} - (a_1 . \theta_w) = 1.60}$ $a_0 = 1.60$
Result	$a_1 = 7.82$ $a_0 = 1.60$

This soil is now calibrated - you can now use these two numbers in place of the default calibrations to convert WET150 readings into volumetric water content ϑ using:

$$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$

See the WET150 SDI-12 Programmer's Guide for details on how to configure the WET150 to output soil moisture readings directly using custom calibrations.

See also Underlying principle on page 59.

Soil Parameter Derivation

Without laboratory equipment, deriving custom soil parameters is difficult to do with any accuracy. We suggest you use the following procedure, but bear in mind that the results should be treated as indicative only:

1   Take a sample of soil (~300ml) and put this in a wide-mouth bottle that has a sealable cap. The quantity of soil is not critical, but needs to be enough so that you insert the WET sensor fully and avoid edge effects, i.e. ~70mm diameter x 75mm high.

2   Add tap water of approximately twice the soil volume (600ml). The conductivity of the tap water is not critical, but the volume needs to be sufficient to saturate the soil and leave enough fluid above the soil to immerse the WET Sensor.

3   Mix **very thoroughly**, preferably by shaking the closed container for ~10 minutes.

4   Let the soil settle for an hour.

5   Measure the permittivity (ε'_w) and conductivity (EC_w) of the free water on top of the soil using the WET150 Sensor,

6   Push the sensor down into the soil (NB Ensure your cable is well connected to avoid water leakage!) and measure the bulk conductivity (EC_b) and permittivity (ε'_b) in the saturated soil below.

7   The soil parameter $\varepsilon'_{\sigma_b=0}$ can then be calculated from the formula:

$$\varepsilon'_{\varepsilon_b=0} = \varepsilon'_b - \frac{\left(\varepsilon'_v \times EC'_b\right)}{EC'_v}$$

Appendix 2

Soil-specific Parameters

This section lists some generic parameters which can be used for improved accuracy in particular soil/substrate types. Best performance will always be achieved by using a set of parameters customised to your specific growing medium and operating conditions. The generic values provided here are designed to give good accuracy across a broad category of soil/substrate types.

Soil type	a_0	a_1	Soil parameter	"Too dry" threshold
Mineral	1.6	8.4	-4[8]	5.7
Organic	1.3	7.7	5.5[9]	8.5
Peat Mix	1.16	7.09	1.8	4.8
Coir	1.16	7.41	0	5.2
Mineral Wool	1.04	7.58	-0.3	2.7

Table 1 - WET150 sensor soil-specific parameters for improved accuracy

By default, the WET150 is shipped with generic parameters that match the generic parameters in Delta-T's WET-2 sensor. For reference these are listed below:

Soil Type	a_0	a_1	Soil Parameter	"Too dry" threshold
Custom	1.6	8.4	0	3
Mineral	1.6	8.4	-8.9	5.7
Organic	1.3	7.7	-12	8.5
PeatMix	1.16	7.09	-8.1	4.8
Coir	1.16	7.41	-1.5	5.2
MinWool	1.04	7.58	-0.3	2.7

Table 2 - WET150 sensor soil-specific parameters for WET-2 default compatibility

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[8] Mineral Soil – tests at Delta-T suggest this figure for ε_0 varies significantly with salinity. The figure given is suggested for soil salinities 100-200mS/m

[9] ε_0 for organic soils suggested for salinities 300-600mS/m

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