User Manual for the

WET150 Sensor

type ***WET150***

WET150-UM-1.1

Delta-T Devices Ltd

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

Introduction

Cables

To meter

Extension cables

To GP2 and other loggers

SDI-12

Industry-standard digital interface, compliant to version 1.3

Connector

Fully waterproof M12 connector -

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

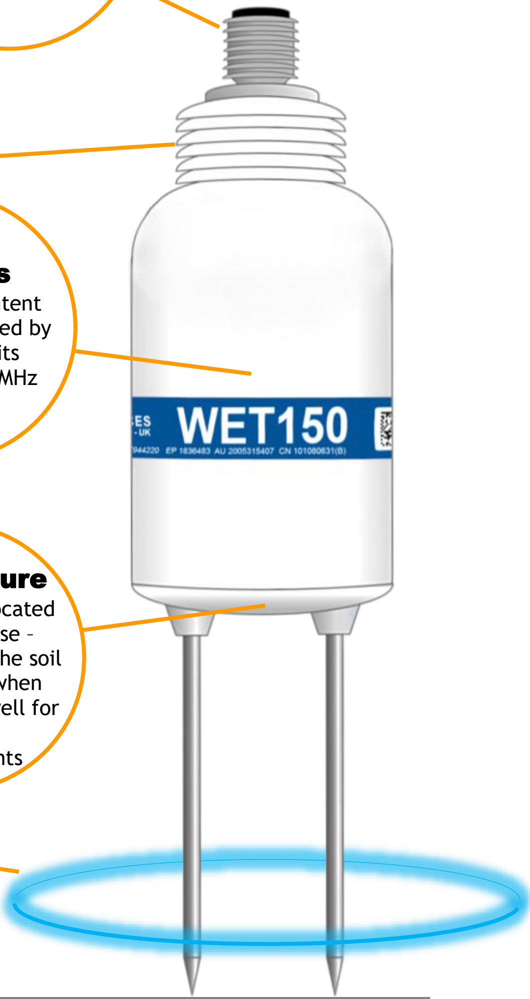
Sophisticated correction algorithms ensure accurate readings across the full range of water content, EC and temperatures

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



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:

- **W**ater Content
- **E**lectrical Conductivity
- **T**emperature

The sensor converts the measured dielectric properties into **Water Content** over the full range, 0 to 100%, being most accurate, ±3%, over 5 to 100% water content and over 0 to 500 mS/m soil bulk conductivity. 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.

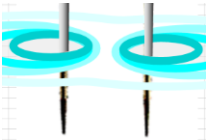
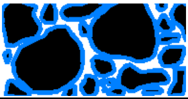
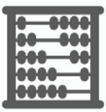
The WET150 Sensor works with the WET150 Meter and the GP2 logger controller.
It can also be used with other SDI-12 loggers, and with SDI-12 fertigation and irrigation control systems.

Advantages of the WET150 Sensor

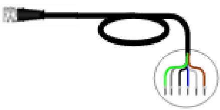
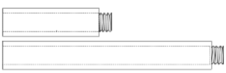
- Fast, accurate, adaptable and easy to use
- Rapid measurements (~1 second) of all 3 parameters
- *In-situ* Pore Water Conductivity measurements
- Easy insertion into growing media and soil
- Works with many different soils and growing media
- Stable, accurate readings from
  5 to 100% water content
  0 to 1200 mS.m^{-1}
  -20 to +50°C
- Lightweight ergonomic design
- Versatile SDI-12 digital output
- Systems integrator friendly
- Wide choice of settings, outputs and units
- Low power for long battery life
- 2-year warranty extends to 5 years if registered on delivery

How the WET150 Sensor works

Measurement Principle

	When you insert the WET150 Sensor into soil and take a reading...
	...it generates a 100 MHz signal...
	...which is applied to the pins and produces a small electromagnetic field within the soil.
	The water content, electrical conductivity, and composition of the soil surrounding the pins...
ε	...determines its **dielectric properties**.
	The WET150 sensor detects these dielectric properties from their influence on the electromagnetic field and calculates ...
	… **Soil Moisture** and **Pore Water Conductivity**. It also records **Temperature** and uses that to improve the accuracy of the other measurements
	… and sends the results, on demand, to either an WET150 meter, GP2 logger-controller or other SDI-12 enabled device

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-NTP**	3-way network T- Piece for connection WET150 and EXT/5W-xx cables
	**ML/EX50** **ML/EX100**	Extension tubes, 50 and 100 cm
	**SM-AUG-100**	Spiral Auger 1.2 m

Care and Safety

- The pins of the WET150 are sharp in order to ease insertion. 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.

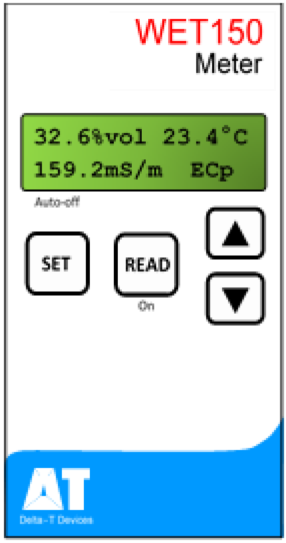
- Take care when attaching cables to ensure that the connectors are clean, undamaged, and <u>properly aligned *before* </u>pushing the parts together.

- 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

Use with a WET150 Meter



Use it to take readings or change the address. Settings for soil type, conductivity units and temperature units can also be changed.

Take a Reading

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, Peat mix, Coir, Min. wool** and **Perlite** 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}, 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 – 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.

See also **WET150 Kit Quick Start Guide**

Temperature

The thermistor in the WET150 is internal to the white body, so it can be slow to equilibrate with the soil temperature. This can affect the EC measurement accuracy as the conductivity of typical plant nutrients changes by ~2% / °C. If for use as a portable sensor, use it **in well-equilibrated environments** where the air temperature doesn't differ significantly from the soil/substrate temperature.

Temperature can be displayed in °C or °F.

Pore Water EC (ECp)

The EC (Electrical Conductivity) of the water in the soil pores is calculated by applying the Hilhorst equation. This is a very useful approximation that works exceptionally well with the WET150 because the sensor measures permittivity and measured bulk electrical conductivity (ECb) in the same sample volume at the same frequency (100MHz). The Hilhorst equation ceases to be a good approximation when there is too little water present, so the meter displays "too dry" instead (typically at <12.5%, as in mineral soil)

ECp can be displayed in mS/m, mS/cm or μS/cm.

Use WET150 Meter to Change Address

➡ Each sensor **must** have a different address on an SDI-12 network or it will not work.

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.

➡ *The WET150 Meter only takes readings from a WET150 sensor.

1. Press [**SET**]

Wakes the Meter and displays the first option in the settings menu

2. Press [▼] twice

Scrolls down to the Address setting menu

3. Press [**SET**]

Selects that menu, and **displays the current SDI-12 address**

4. Press [▼] or [▲] as often as necessary

Scrolls to the desired target address

5. Press [**SET**]

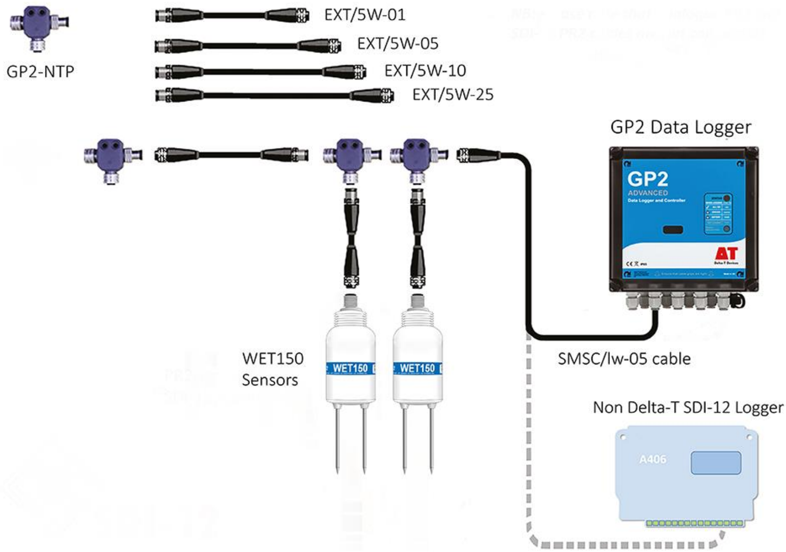
Attempts to set that address

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**

Network Cabling



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

These Delta-T extension cables are terminated in M12 thumb-screw connectors, male at one end, female at the other. 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. An advantage of the M12 connector system is that it is 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 whole 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 thumb-screw / collar may allow water ingress into the cable or sensor, leading to premature failure which is not covered by warranty.

M12 plugs with screw connectors are available for adding other sensors to the SDI-12 network.
See also: **SDI-12 for GP2 User Manual**

NOTE

Before connecting on a network each WET150 sensor must be individually set up with a unique address. So 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

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 (so 320 m 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

Connecting to loggers or 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 and the WET150 Meter.

Wiring

GP2 Logger Wiring: See pages 16 and 17

Other loggers and systems wiring:

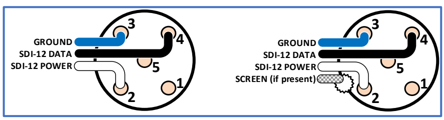
Wire colour		Logger or controller	SDI-12 function	M12 connector pin
Brown		Not connected		1
White		+12V 0.5A	Network power	2
Blue		GND	Ground (for power and data)	3
Black		DATA	Data (send and receive)	4
Grey		Not connected		5
Green		Not connected **	(Cable screen) **	Shell / nut

** 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 data corruption.

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 pages 12, 32 and 33 of the **SDI-12 for GP2 User Manual**



See **Power supply** on page 26

GP2 wiring 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.

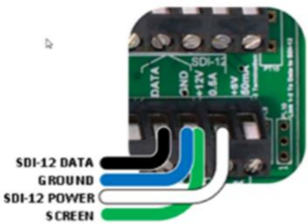
SDI-12 sensors typically require a 3-wire connection: Power, Ground and Data. This is the case with the WET150 but the cabling system includes additional wires which are not normally used within an SDI-12 network.

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	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 data corruption. The figure on the right illustrates the wire and terminal connections with the optional green screen wire.



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.

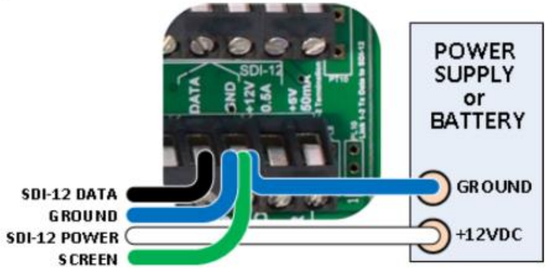
Power is automatically supplied when the WET150 sensor is selected in the DeltaLINK program.

GP2 wiring 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.

Give Each WET150 a Unique Address

If two sensors have the same address an SDI-12 network **will not work**. So, give each WET150 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 is best to change it.
It can be any one of the following 62 addresses: -
0 to 9, a to z or A to Z.

Use either a **WET150 Meter** connected directly to a WET150 sensor - see page 12, 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.

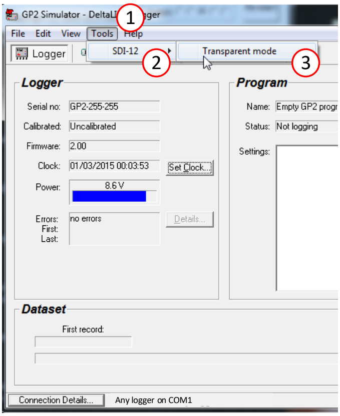
See also: the **GP2 User Manual**
SDI-12 for GP2 User Manual
WET150 SDI-12 Programmer’s Guide

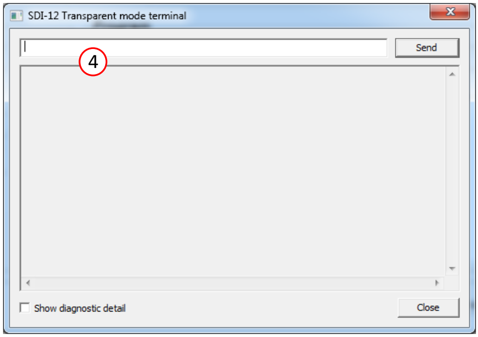
1 Open DeltaLink Transparent Mode

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 and putting more than one sensor on the network with the same address will crash the network.

Make a note of the address and the serial number.

Later when you have finished giving each sensor a unique address, Close the Transparency Mode 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. See also Create GP2 Program on page 21.

Advanced users only

You can change the default **Measurement name** to add useful metadata – such as the address, e.g. *Theta* becomes *Theta Z* and so see the address displayed in the results. 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

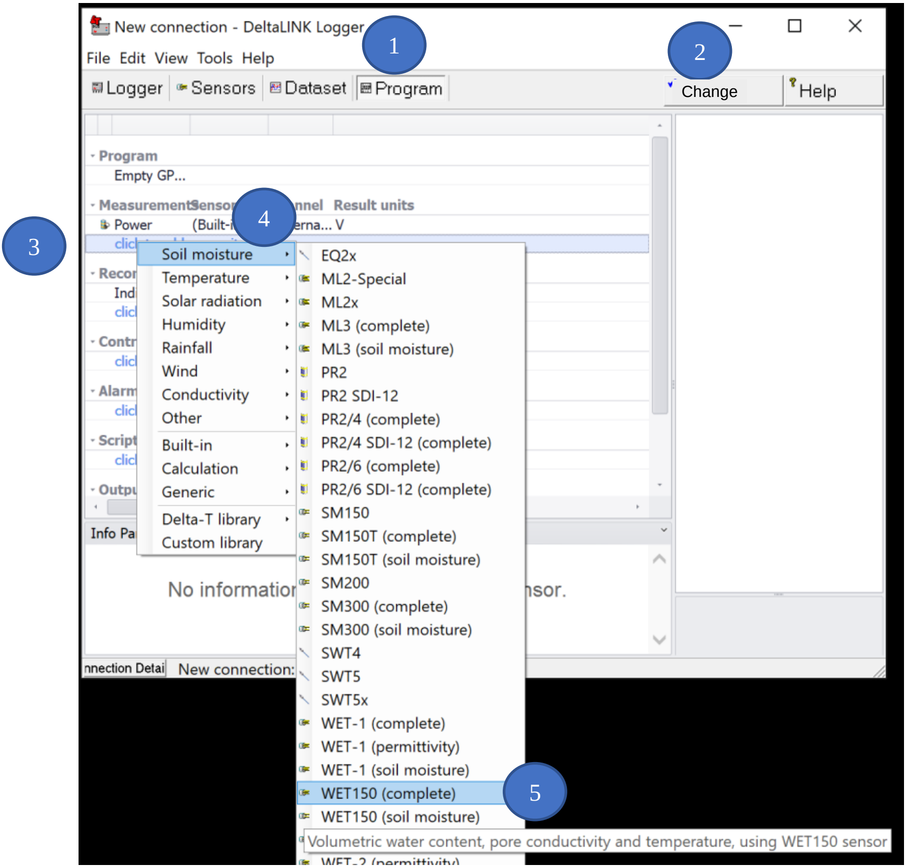


Illustration: showing steps in the creation of a WET150 soil moisture sensor measurement type in a GP2 program.

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

4. Select **WET150 (complete). t**his will create three sensor measurement types for soil moisture, electrical conductivity and temperature, each with a default 1 hour recording period.

5. Select **the Address** to that of the WET150 sensor, as described on page18.   You should now see the following:

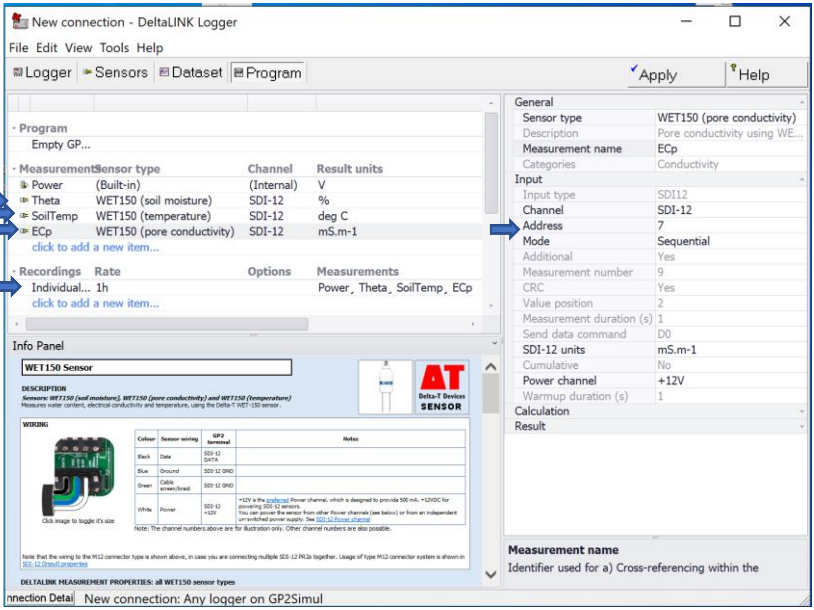


Illustration: showing three sensor measurement types added to take readings from a single WET150, for soil moisture, pore water conductivity and temperature. These all have the same SDI-12 address, which in this example has been changed to 7 from the default 0 address. The default measurement period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

2: Sensor type Settings

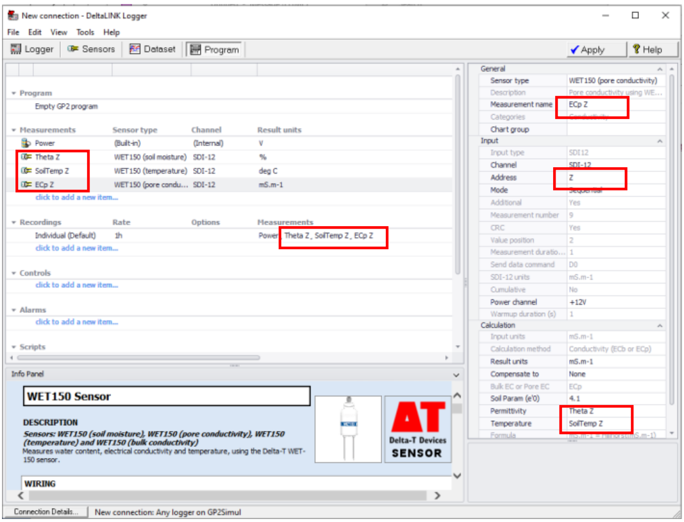
This explains the Measurement and Parameter settings supplied in the WET150 sensor types in the DeltaLINK sensor library.

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 **Give Each WET150 a Unique Address** on page 18.

4. **Mode**: The default WET150 sensor type uses the SDI-12 **Sequential** data measurement and reporting method.
   See also **Concurrent Measurements** on page 27.

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, Perlite, 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.

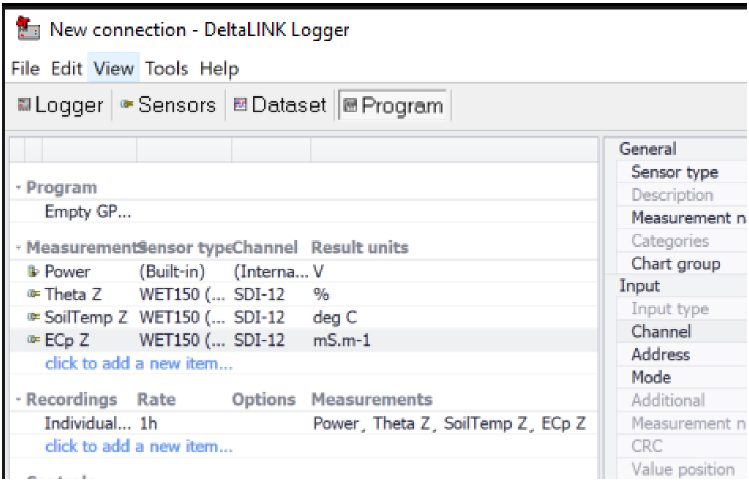


Illustration: DeltaLINK, GP2 Program tab with a default Recording interval set to 1 hour for each of the defined Measurements.

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.

Power supply

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.

Maximum cable length

See page 14

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)

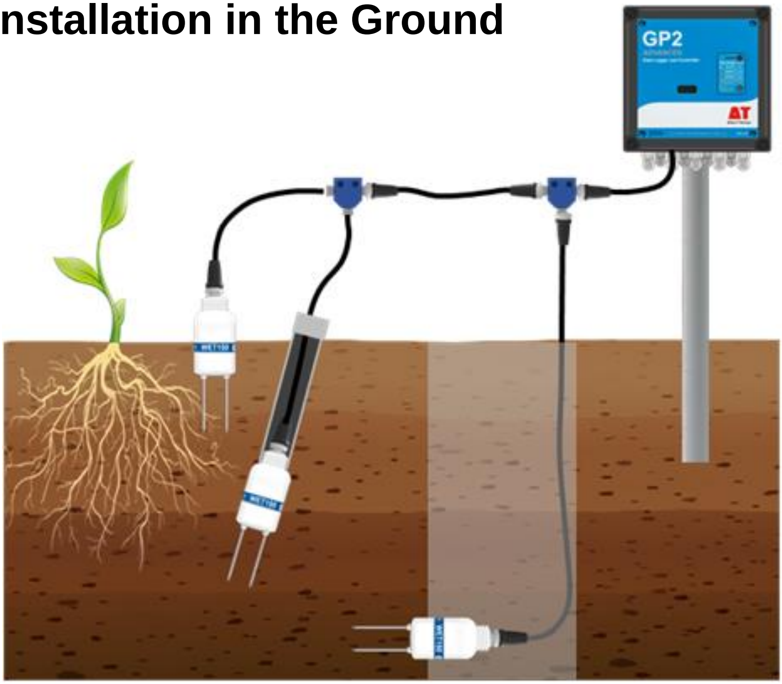
Other data loggers

The default setting for WET150s is to output the measured soil permittivity. If using this default option either convert the data to soil moisture units after logging, or program your data logger to convert the output automatically before saving the data, using the information supplied in the **Conversion to Soil Moisture** section.

Alternatively, by using one of the available SDI-12 commands, a WET150 can be instructed to output data in soil moisture units, for a range of soils.

See **WET150 SDI-12 Programmers Guide.pdf**.

Installation in the Ground



See this https://youtu.be/ZRMUkiy-f3g

Surface installation and spot measurements

- 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, you have probably 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.

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

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 an introduction to SDI-12 commands

The format of SDI-12 commands and responses can become complicated in real-world use on a network of many devices.

Fortunately, just two simple commands are required for changing sensor addresses:

- Address Query – find out the existing address of the single WET150 connected to the GP2
- Address Assign – change the existing address to a new address

The following examples explain what you need to type in the command entry box and how to interpret responses in the terminal window. Full details of these and all SDI-12 commands used by the WET150 are given in the **WET150 SDI-12 Programmer's Guide** available as a PDF at www.delta-t.co.uk

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 connected to the GP2, particularly if you are configuring brand new sensors which may all be configured 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 WET150v01 D1234567`	

The visible terminal window character string "**`dI!d13Delta-T WET150v01 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
`v01`	Sensor firmware version
`D1234567`	WET150 serial number

Table of default / pre-configured measurements

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.

The factory defaults for the ten pre-configured measurement sets (shown only using the M command for clarity) are:

Command	Response parameters	Units	Notes
`aM!`	ε_r (permittivity)	(none)	
	EC_p (pore water EC)	$mS.m^{-1}$	Compensated to 25°C linearly at 2%/°C, soil parameter= 4.1
	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, soil parameter= 4.1
	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, soil parameter= 4.1
	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, soil parameter= 4.1
	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, soil parameter= 4.1
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	$mS.m^{-1}$	

(table continued)

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, soil parameter = 4.1
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	$mS.m^{-1}$	
aM6!	Water content	%vol	Using **Perlite** soil-type calibration
	EC_p (pore water EC)	$mS.m^{-1}$	Compensated to 25°C linearly at 2%/°C, soil parameter = 4.1
	T	°C	
	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	$mS.m^{-1}$	
aM7!			Blank
aM8!			Blank
aM9!	ε_r (permittivity)	(none)	
	EC_b (bulk EC)	$mS.m^{-1}$	
	T	°C	

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

Note about Pore EC (EC_p) calculations:

Failure to set the correct EC soil-parameter value will result in incorrect measurement results, particularly as soils become drier. Note that in very dry soils it is not possible to calculate EC_p reliably, therefore an error code value of -8020 is returned instead. Using the default soil-parameter value of 4.1 and the generic soil type calibrations, the lower soil moisture limit for ECp calculations are:

Generic soil-type calibration	Lower limit soil moisture content for EC_p calculation
Mineral	12.67 %vol
Organic	17.72 %vol
PeatMix	21.22 %vol
Coir	20.30 %vol
MinWool	21.43 %vol
Perlite	24.57 %vol

For further SDI-12 commands see the **WET150 SDI-12 Programmer's Guide**.

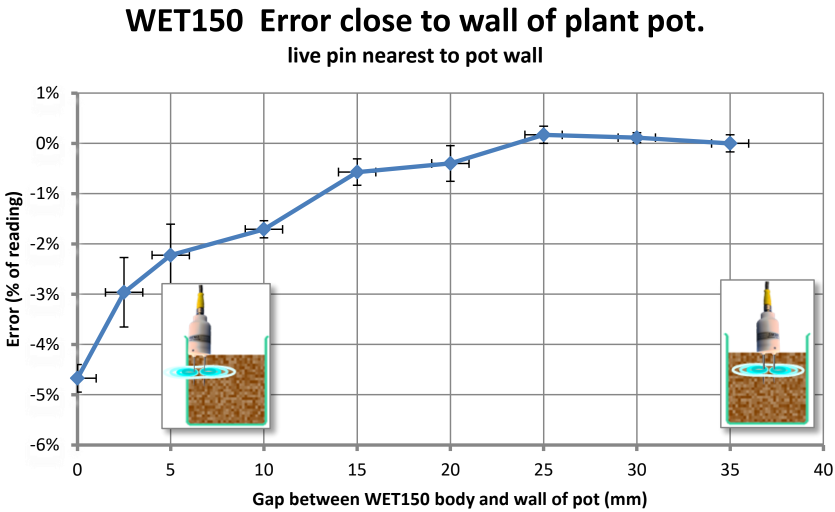
Specifications

Volumetric Water Content (%vol)	
Accuracy	**± 3%** from 5 to 100% vol, EC_b 0 to 500 mS/m (with a calibration matching the soil / substrate)
Operating range	0 to 100% vol
Soil conductivity (ECb))	
Accuracy	**±(10 mS/m + 6%)** from 0 to 1200 mS/m
Operating range	0 to 2000 mS/m
Temperature *(WET150 must be fully buried to accurately measure soil temperature)*	
Accuracy	± 1°C
Range	Accurate range: -20 to+ 50°C Full range: -20 to +60°C
Operating specifications	
Interface	SDI-12 version 1.3
Maximum cable length[1]	>600 m see page 14
Power requirement	6 to 20 V, ~22 mA over 12 ms see page 26
Operating range	-20 to +60°C (sensor does not detect ice)
Environmental	IP68
Sample volume	55 x 70 mm diameter
Dimensions	143 x 40 mm diameter
Weight	77 gm (without cable)

[1] On an SDI12 network

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.



Trouble Shooting

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*.

See Note about Pore EC (EC_p) calculations: on page 39 for more information.

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

See also: Technical Support on page 62

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 the perfect 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
Granite	7 – 9
Water	80.4

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

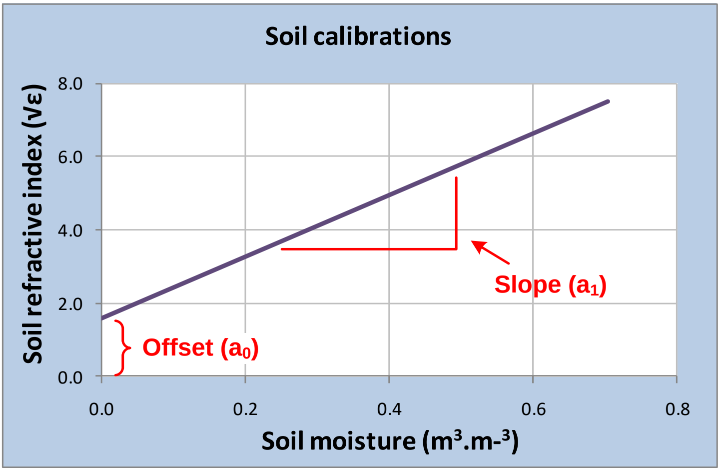
Converting permittivity to water content

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:

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

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



Note that:

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

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

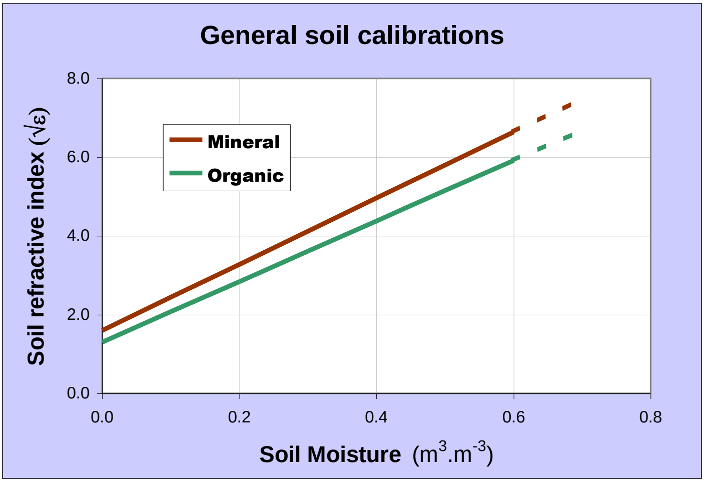
Real soil a_0 and a_1 values can vary significantly from these guidelines when they are affected by other factors – in particular, bound water in clay may result in higher values of a_1.

Generic soil calibrations

Most soils and substrates can be characterised simply by choosing one of the following generic soil types for measurements of water content.

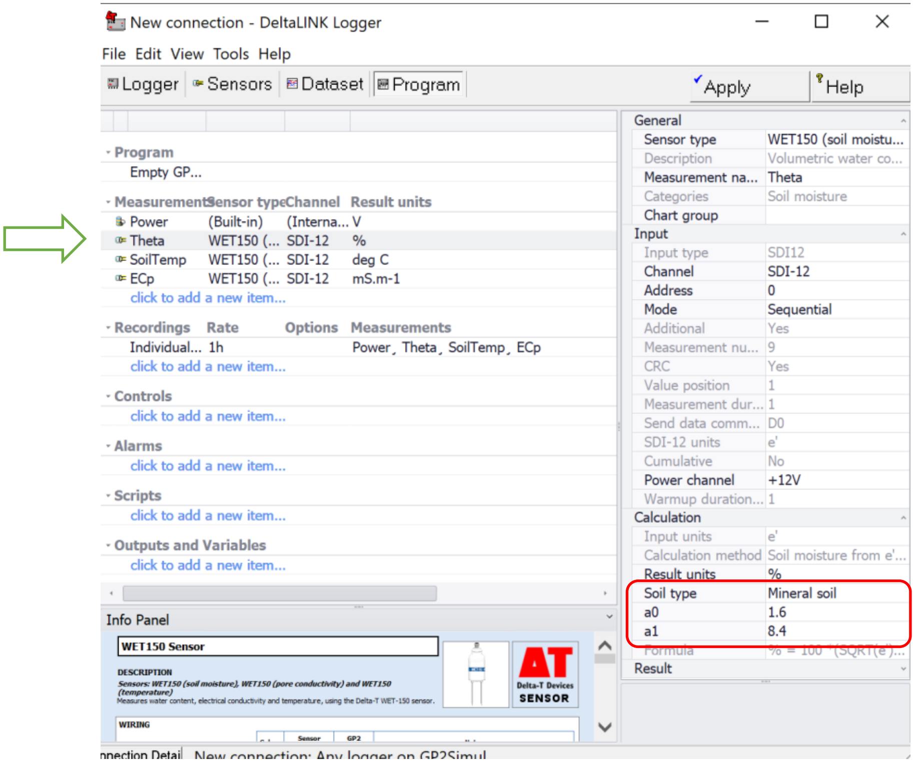
Soil type	a_0	a_1
Mineral	1.6	8.4
Organic	1.3	7.7
PeatMix	1.16	7.09
Coir	1.16	7.41
MinWool	1.04	7.58
Perlite	1.06	6.53

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 56



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 46). The pre-configured WET150 measurement sets and SDI-12 commands assigned to these generic soil types are given in the tables following page 36.

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 63.

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.
See the **WET150 SDI-12 Programmer's Guide** for more information on using soil-specific a_0 and a_1 values for outputting water content measurements directly from the WET150.

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 finally 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,

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

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:

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

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 $\varepsilon_0 = 8.854\ 10^{-12}$ F m^{-1}.

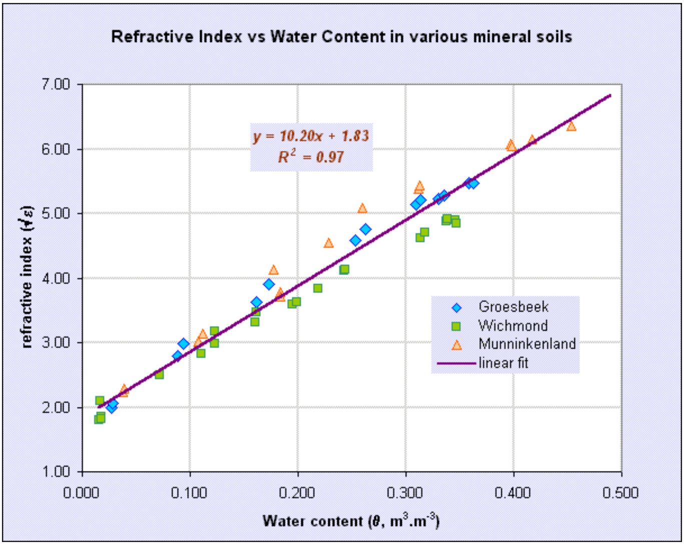
Note: in the remainder of this theory we've used the symbol σ *instead of* EC *for the electrical conductivity, in order to simplify the appearance of the equations.*

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:

$$\sqrt{\varepsilon} = a_0 + a_1 \cdot \theta \qquad \textbf{[3.]}$$

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:

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

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:

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

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 is 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:

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

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:

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

Note that $\varepsilon_{\sigma_b=0}$ is a complex value and includes dielectric and ionic loss. However since σ_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:

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

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:

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

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:

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

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:

$$G = \sigma_{\mathrm{p}} g(\theta)\kappa \qquad \textbf{[11.]}$$

and

$$C = \varepsilon_0 \left(\varepsilon'_{\sigma_{\mathrm{b}}=0} + \varepsilon'_{\mathrm{p}}\, g(\theta)\right)\kappa \qquad \textbf{[12.]}$$

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

$$\sigma_{\mathrm{b}} = \sigma_{\mathrm{p}} g(\theta) \qquad \textbf{[13.]}$$

and

$$\varepsilon'_{\mathrm{b}} = \varepsilon'_{\sigma_{\mathrm{b}}=0} + \varepsilon'_{\mathrm{p}}\, g(\theta) \qquad \textbf{[14.]}$$

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

$$\sigma_{\mathrm{p}} = \frac{\varepsilon'_{\mathrm{p}}\, \sigma_{\mathrm{b}}}{(\varepsilon'_{\mathrm{b}} - \varepsilon'_{\sigma_{\mathrm{b}}=0})} \qquad [15.]$$

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 $\varepsilon'_{\sigma_{\mathrm{b}}=0}$ can be calculated from the ε'_b and σ_b values measured at two arbitrary free water content values.

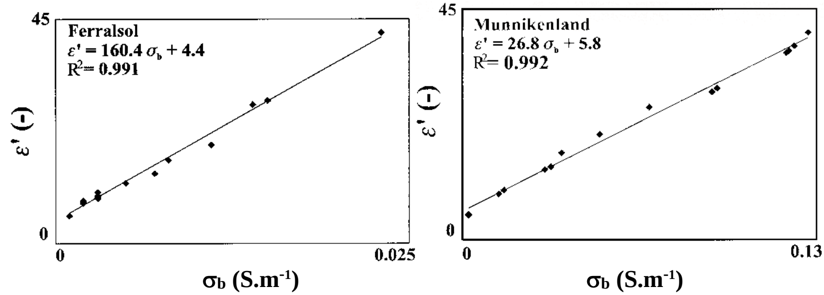


Fig. 1 Examples of the relationship between ε'_b and σ_b, showing the offset $\varepsilon'_{\sigma_b=0}$ for two different soils.

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 $\theta > 0.10$.

References

- Topp, G. C., J. L. Davis, A. P Annan (1980). Electromagnetic determination of soil water content. *Water Resour. Res* **16**(3) 574-582
- Whalley, W R (1993). Considerations on the use of time-domain reflectometry (TDR) for measuring soil moisture content. *Journal of Soil Sci.* **44**, 1-9
- White, I, Knight, J H, Zegelin, S J, and Topp, G C (1994). Comments on 'Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content' by W R Whalley. *Journal of Soil Sci*. **45**, 503-508
- Roth, C H, Malicki, M A,and Plagge, R. (1992). Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements. Journ*al of Soil Sci*. **43**, 1-13
- Knight, J.H. (1992). Sensitivity of Time Domain Reflectometry measurements to lateral variations in soil water content.
- Gregory, A.P., Clark, R.N. (2012) Tables of the Complex Permittivity of Dielectric Reference Liquids at Frequencies up to 5 GHz. *NPL REPORT MAT 23.*
- Hilhorst, M.A. (1998) Dielectric characterisation of soil*. Doctoral Thesis*, ISBN 90-5485-810-9, Wageningen Agricultural University, Wageningen, The Netherlands.
- Hilhorst, M.A. (2000) A Pore Water Conductivity Sensor. *Soil Science Society of America Journal.* **64**, Issue 6, 1922-1925
- Hübner,C., Kaatze, U. (2016) Electromagnetic Moisture Measurements. *Universitätsverlag Göttingen.*
- Kaatze, U., Uhlendorf, V. (1981) The dielectric properties of water at microwave frequencies. *Zeitschrift für Phys. Chem.,* Neue Folge, Bd. 126, 151-165.
- Mualem, Y., Friedman, S.P. (1991) Theoretical prediction of electrical conductivity in saturated and unsaturated soil. *Water Resources Research,* **27**, 2771-2777
- Malicki, M.A., Walczak, R.T., Koch, S., Flühler, H. (1994) Determining soil salinity from simultaneous readings of its electrical conductivity and permittivity using TDR. Proceedings: *Symposium on TDR in Environmental, Infrastructure and Mining Applications*, September 1994, held at Northwestern University, Evanston, Illinois, USA. Special Publication SP 19-94, US Department of Interior Bureau of Mines, 328-336
- Nyfors, E., Vainikainen, P. (1989) *Industrial microwave sensors*. Artech Hous, Norwood, USA.
- Peyman, A., Gabrriel, C., Grant, E.H. (2007) Complex permittivity of sodium chloride solutions at microwave frequencies. *Bioelectromagnetics* **28**:264-274
- Rhoades, J.D., Shouse, P.J., Alves, W.J., Manteghi, N.A., Lesch, S.M. (1990) Determining soil salinity from soil electrical conductivity using different models and estimates, *Soil Science Society of America Journal*, **54**, 46-54.

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. 0.02 $m^3.m^{-3}$ 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

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

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 (= $1 g.cm^{-3}$), 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}).

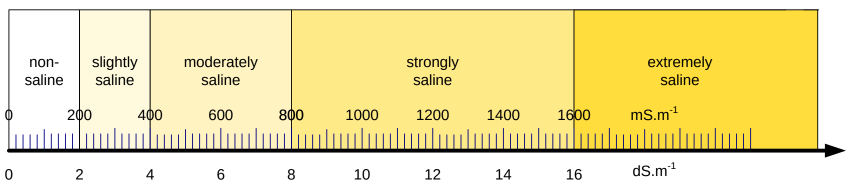
The following conversions apply:

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

= 0.01 mS.cm^{-1}

= 10 µS.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 ($\boldsymbol{L}$) and cross-sectional area ($\boldsymbol{A}$) of the measurement cell.

Conductivity and *conductance* are related by the formula

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

$= G.C$ (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:

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

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

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 20 MHz, 25°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.

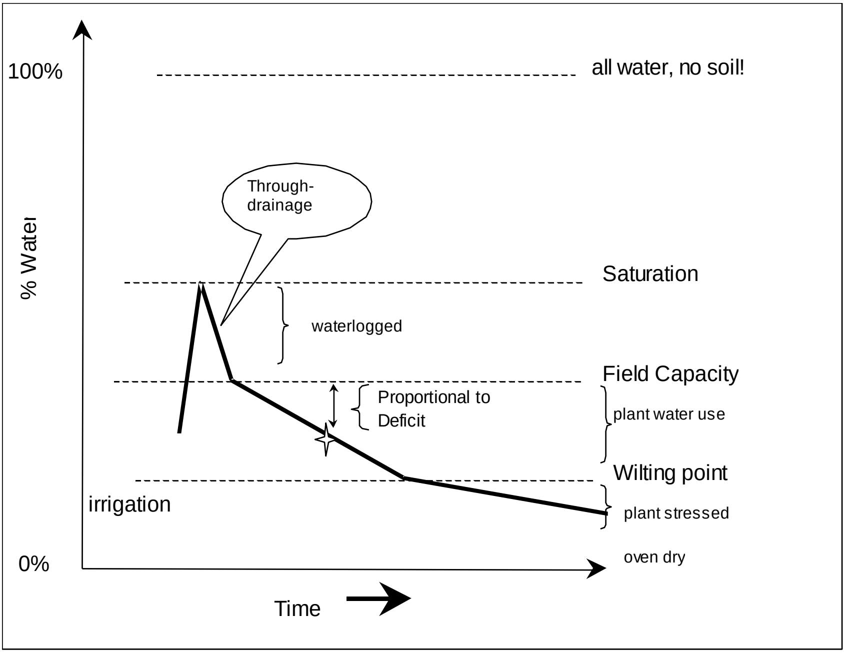
Field Water Capacity (or Field Capacity)

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 0.45$m^3.m^{-3}$ 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

Terms and Conditions of Sale

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

Service and Spares

Users in countries that have a Delta-T Distributor or Technical Representative should contact them in the first instance.

Spare parts for our own instruments can be supplied from our works. These can normally be despatched within a few working days of receiving an order.

Spare parts and accessories for sensors or other products not manufactured by Delta-T, may have to be obtained from our supplier, and a certain amount of additional delay is inevitable.

No goods or equipment should be returned to Delta-T without first obtaining the agreement of Delta-T or our distributor.

On receipt of the goods at Delta-T you will be given a reference number. Always refer to this reference number in any subsequent correspondence. The goods will be inspected and you will be informed of the likely cost and delay.

We normally expect to complete repairs within one or two weeks of receiving the equipment. However, if the equipment has to be forwarded to our original supplier for specialist repairs or recalibration, additional delays of a few weeks may be expected. For contact details see below.

Technical Support

Users in countries that have a Delta-T distributor or technical representative should contact them in the first instance.

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.

Contact details

Technical Support
Delta-T Devices Ltd
130 Low Road
Burwell
Cambridge CB25 0EJ
England (UK)

Tel: +44 1638 742922
Fax: +44 1638 743155
E-mail: tech.support@delta-t.co.uk
sales@delta-t.co.uk
Web: www.delta-t.co.uk

Appendix

Soil-specific Calibration

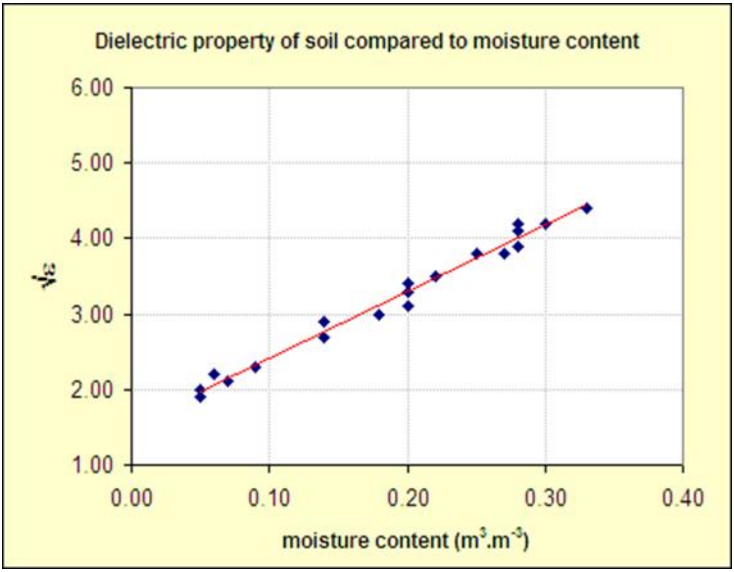
This note describes two techniques for generating soil-specific calibrations:

- 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 How it works on page 43)



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:

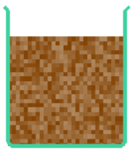
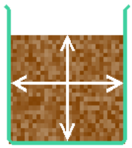
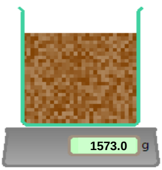
$$\sqrt{\varepsilon} = a_0 + a_1 \times \theta$$

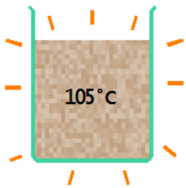
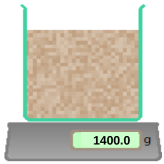
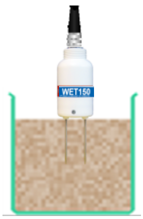
Laboratory calibration for non-clay soils

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 = 960.0*ml***
	Weigh the sample, including the beaker. ***W_w* = 1573*g***

	Insert WET150 into the sample, press [Read] on the meter and record the permittivity reading (ε'). $\varepsilon_w = 9.06$, I.e. **$\sqrt{\varepsilon_w} = 3.01$**
	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.
	Weigh the dry sample in the beaker. **$W_0 = 1400g$**
	Re-insert the WET150 into the dry sample and again record the permittivity reading. $\varepsilon_0 = 2.56$, I.e. **$\sqrt{\varepsilon_0} = 1.60$**
Calculate a_0	Since the water content of the dry soil, $\theta_0 = 0$, 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	$a_1 = (\sqrt{\varepsilon_w} - \sqrt{\varepsilon_0})/(\theta_w - \theta_0)$ $= (3.01 - 1.60)/(0.173 - 0)$ $= 7.82$

	$a_1 = 7.82$
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.

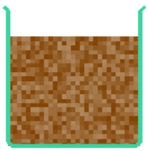
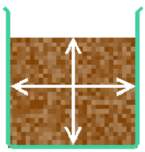
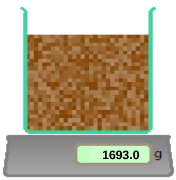
See also **Underlying principle** on page 63.

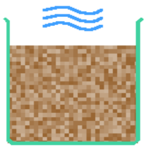
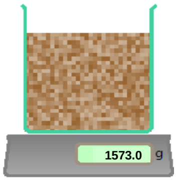
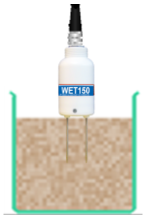
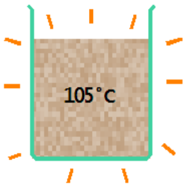
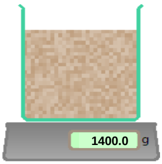
Laboratory calibration for clay soils

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 (≥ 1.0 litre)
- Weighing balance (accurate to < 1g)
- Temperature controlled oven

Process	*Notes and example*
	Collect a <u>wet</u> 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. ε_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: $\theta_w = (W_w - W_0)/L_s = (1693 - 1400)/960 = 0.305$ θ_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 $a_1 = \frac{\sqrt{\varepsilon_w} - \sqrt{\varepsilon_m}}{\theta_w - \theta_m} = \frac{3.99-3.01}{0.305-0.180} = 7.82$ **a_1 = 7.82**
Calculate a_0	and $a_0 = \sqrt{\varepsilon_w} - (a_1 . \theta_w) = 1.60$ **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 63.

Index