I. Description of Sensor and Measurements

The digital sensors, 5TE and 5TM, are designed to measure the water content, electrical conductivity (5TE only), and temperature of soil and growing media.

II. Features:

The 5TE sensor measures soil moisture, soil temperature, and bulk electrical conductivity (EC) and the 5TM measures soil moisture and soil temperature. These fundamental measurements are needed for a variety of plant studies. By combining these measurements into a single sensor, it allows for more data logger ports to be used for additional environmental measurements. Volumetric water content is obtained by measuring the dielectric constant (ε_a) of the media through the utilization of capacitance/frequency domain technology while EC (5TE only) is obtained using two stainless steel screws. The digital sensors incorporate high frequency oscillation, allowing the sensor accurate measurements of soil moisture in any soil or soilless media with minimal salinity and textural effects.

III. Measurement Specifications:

VWC:

Accuracy: **ε_a:** ±1 ε_a (unitless) from 1-40 (soil range), ±15% from 40-80
VWC:
• Using Topp equation: ±0.03 m^3/m^3 (±3% VWC) typical in mineral soils that have solution electrical conductivity < 10 dS/m
• Using medium specific calibration: ±0.01 - 0.02 m^3/m^3 (± 1-2% VWC) in any porous medium.

Resolution: ε_a: 0.1 ε_a (unitless) from 1-20, < 0.75 ε_a (unitless) from 20-80 VWC: 0.0008 m^3/m^3 (0.08% VWC) from 0 to 50% VWC

Range: Apparent dielectric permittivity (ε_a): 1 (air) to 80 (water)

Bulk Electrical Conductivity (5TE only):

Accuracy: ±10% from 0-7 dS/m, user calibration required above 7 dS/m

Resolution: 0.01 dS/m from 0-7 dS/m, 0.05 dS/m from 7-23 dS/m

Range: 0-23 dS/m (bulk)

Temperature:

Accuracy: ±1°C

Resolution: 0.1°C

Range: -40°C to +50°C

IV. General Specifications:

Dimensions:	10 x 3.2 x 0.7 cm
Probe Length:	5.2 cm
Dielectric Measurement Frequency:	70 MHz
Measurement Time:	150 ms
Power:	3.6 - 15 VDC, 0.3 mA quiescent, 10 mA during 150 ms measurement
Output:	Serial TTL, 3.6 Volt Levels or SDI 12
Operating Temperature:	-40°C to +50°C
Connector Types:	3.5 mm "stereo" plug or stripped and tinned lead wires (3)
Cable Length:	5m standard; custom cable length available upon request

Input / Output Circuitry

A single line is used for both transmit and receive. A 10 uH inductor and a 510 ohm resistor are in series with the RXD/TXD line on the microprocessor with a 220 pF capacitor to ground. The resistor and capacitor provide input protection. The inductor minimizes RF interference.

Sensor Excitation

The sensor connects through a 3 wire cable with a stereo connector or bare wire interface. The three connections are Excitation, Ground, and Serial Out. The connector tip (white wire) is Excitation, the connector base (shield) is ground, and the intermediate ring (red wire) is Serial Out. The excitation is 3.6 to 15 volts. Current drain during the water content measurement (approximately 10 ms in duration) can be as high as 45 mA. Be sure that the selected power supply can provide this current without being pulled below the 3.6 V level.

When excitation voltage is applied the sensor begins its measurement sequence. Within about 50 ms of excitation three values are transmitted on the serial out line. On PCB’s with a data stamp of May 2008 or newer, three values plus additional meta data are transmitted on the serial out line. The power MUST be removed and reapplied for a new set of values to be transmitted. If power is applied continuously the probe enters SDI-12 mode.

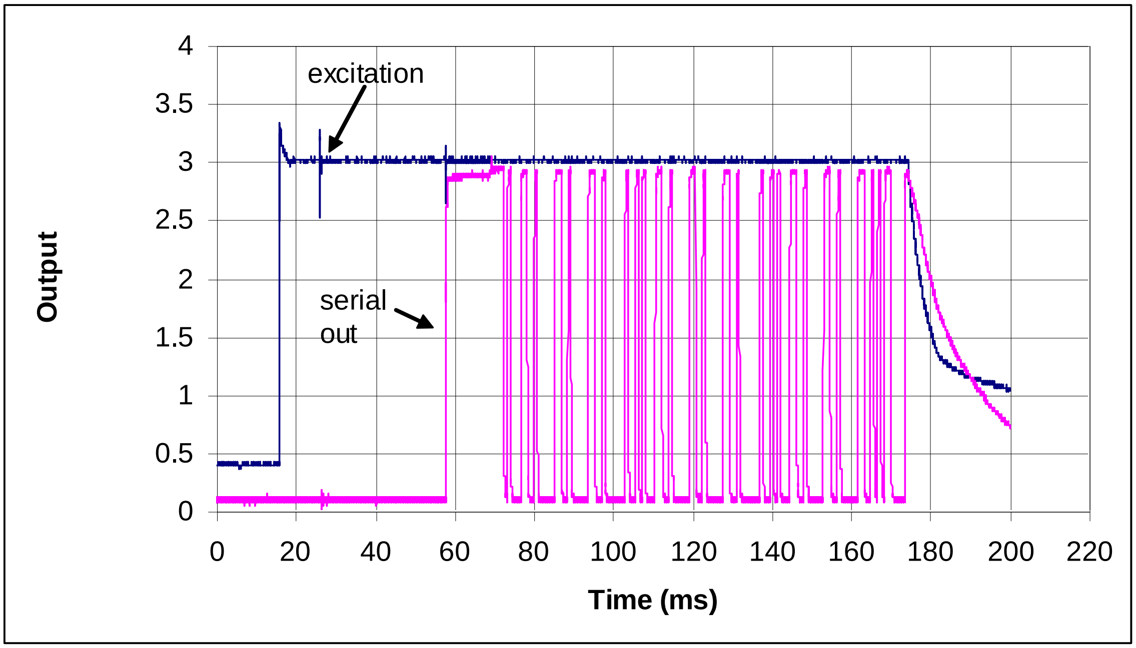

Figure 1. Excitation and serial output stream. Output levels are not absolute. Both excitation and output are zero initially. Approximately 40 ms after the excitation goes high the serial out line goes high. It stays high for 15 ms, and then goes low for the start bit of the serial stream. Twelve characters are shown: 100 100 100/r. When the carriage return character is received the excitation is shut off.

TTL Communication

The serial out uses 1200 baud asynchronous CMOS with 8 data bits, no parity, and one stop bit. The voltage levels are 0 - 3.6 V and the logic levels are TTL (active low). Each data byte consists of a start bit (low), 8 data bits (least significant bit first), and a stop bit (high).

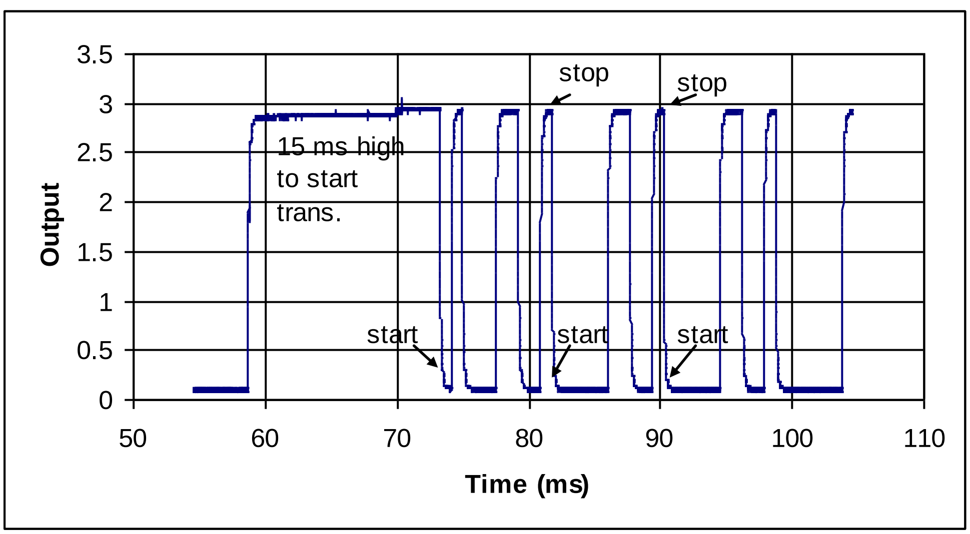

Figure 2. Expansion of first few bits of serial stream from Fig. 1 showing the start and stop bits and the data bits. Baud rate is 1200, so one byte (8 data bits plus start and stop) takes 8.33 ms. Bytes are transmitted lsb (least significant bit) first, so the first character, 10001100 represents 00110001 or 0x31 which is ASCII 1. The next character is 00001100 which is 0x30 or ASCII 0.

TTL Format Description

The data string output by the sensor should be in a format similar to the one below:

56 432 645<0D>zG<0D><0A>

Section	**Description**
`56`	Raw dielectric output in the format raw output = dielectric * 50. Values range from approximately 50 to 4095. To convert to VWC in mineral soil, we recommend the well known Topp equation (Topp et al, 1980): $\theta = 4.3X10^{-6} * \varepsilon^{3} - 5.5X10^{-4} * \varepsilon^{2} + 2.92X10^{-2} * \varepsilon - 5.3X10^{-2}$ In this example, 56 this is the raw apparent dielectric reported. Dividing this by 50 gives a value of 1.12. This is an appropriate value for a sensor measuring air.
`432`	Electrical conductivity in mS/cm multiplied by 100. Divide this number by 100 to get mS/cm (or dS/m). This value is already temperature corrected within the 5TE probe using the temperature correction outlined by the US Salinity labs Handbook 60. Raw values for EC in tap water can range from 10 to 80 (0.1 to 0.8 dS/m). On 5TM's this value is zero and should be ignored. In this example, 432 is the raw bulk electrical conductivity reported. Dividing by 100 gives a value of 4.32 mS/cm.
`645`	Temperature. This number is 10*T + 400, where T is the degrees Celsius. To convert it to temperature, subtract 400 and divide by 10. Room temperature gives a value between 600 and 650. In this example, 645 is the raw temperature value reported. Subtracting by 400 and dividing by 10 gives us a temperature of 24.5°C.
`<0D>`	This carriage return character signals the end of the measurement string and start of the meta data string.

Everything below is this line is meta data:

`z`	Sensor Type. This character is used to indicate the sensor type. z is used for 5TE sensors, and x is used for 5TM sensors.
`G`	Checksum. This one character checksum is used in our instruments to ensure that the data transmitted are valid. The checksum is used for sections listed above: `56 432 645<0D>z` See the following function for an example of how to implement the checksum algorithm in C.
`<0D><0A>`	The carriage return and line feed are used to signal the end of the meta data section and the end of the transmission.

Here is an example of how to calculate the checksum (crc) in C. In this case, the string passed to the function would be: "`56 432 645<0D>z`" and the returning value would be the character 'G'.

```
char CalculateChecksum(char * Response){
    int length, sum = 0, i, crc;

    // Finding the length of the response string
    length = strlen(Response);

    // Adding characters in the response together
    for( i = 0; i < length; i++ )
        sum += Response[i];

    // Converting checksum to a printable character
    crc = sum % 64 + 32;

    return crc;
}
```

TTL Typical Outputs
Typical output while the sensor is suspended in air 20°C will be *approximately*:
50 0 600, which translates into a dielectric = 1, EC = 0, T = 20°C.
If the sensor is fully suspended in 20C tap water, the outputs will be *approximately*:
4000 50 600, which translates into dielectric = 80, EC = 0.5 dS/m, T = 20°C. Note that the raw dielectric output in water can range from 3400 to 4095, and that the EC of tap water is highly variable depending on the source.

SDI-12 Communication
When power is applied to the probe it transmits the data values as previously discussed. It then enters a low power state waiting for input. The commands it recognizes follow the SDI-12 protocol (see http://www.sdi-12.org for detailed information on the SDI-12 protocol). Communication is at 1200 baud, but logic levels are opposite to those for the initial transmission (start bit high; stop bit low) to conform to SDI-12 protocol. A communication starts with a SDI-12 break or any transmitted character. This "wakes" the sensor. No activity on the communication line for approximately 10 s returns it to sleep mode (30 ua current drain). Since there is only one data line which is used for both transmit and receive, the host must transmit its message and then quickly switch to receive mode to monitor the response. All commands are of the form <address><command><parameters>! The "!" is always the termination character for every command. Multiple device addresses are allowed so several probes can be connected to one port if they have different addresses, and each can be addressed separately. The "?" can be used in place of an address, in which case all devices connected to the port will respond.

Some Commonly Used SDI-12 Commands:

Command	**Description**
A<new address>	change the sensor address; an address can be an integer 0..9 or letter, A..Z, a..z
I	returns probe ID
M	measure probe values
D0	return measured values

SDI-12 Examples:

The characters in bold are what was sent to the sensor.

1I!113DECAGON 5TE 301

Identify sensor with address of 1; Return: Sensor Address(1), SDI12 Version (13), COMPANY (DECAGON), SENSOR TYPE (5TE), SENSOR VERSION (301)

1M!10013

Measure parameters of sensor with address of 1; Return: sensor address is 1, data are ready in 001 ms, 3 values will be sent

1D0!1+22.00+1.30+21.8

Send the values; Return: sensor address is 1, 22.00 for water content ($\varepsilon = 22.0$), 1.30 mS/cm for EC, 21.8°C for temperature

?!0

This returns the sensor address; Return: sensor address is 0

0A1!1

Change the sensor address to 1; Starting address is 0. Return: new sensor address is 1

SDI-12 Compliance:
Decagon's SDI-12 sensors recognize all SDI-12 commands outlined in Version 1.3 of the SDI-12 Protocol (see http://www.sdi-12.org for more detailed information).

Here is a list of differences between the SDI-12 standard and Decagon's SDI-12 sensors:

- Upon excitation, a TTL string is printed prior to enabling SDI-12 (takes around 75ms).
- Parity Bits are ignored.
- R & RC Commands return a reading after about 50ms.
- Timeout / Power Down is around 5 seconds instead of 100ms.
- After Timeout / Power Down, sensors may respond to a break that's less than 6.5 ms.

SDI-12 Diagrams:

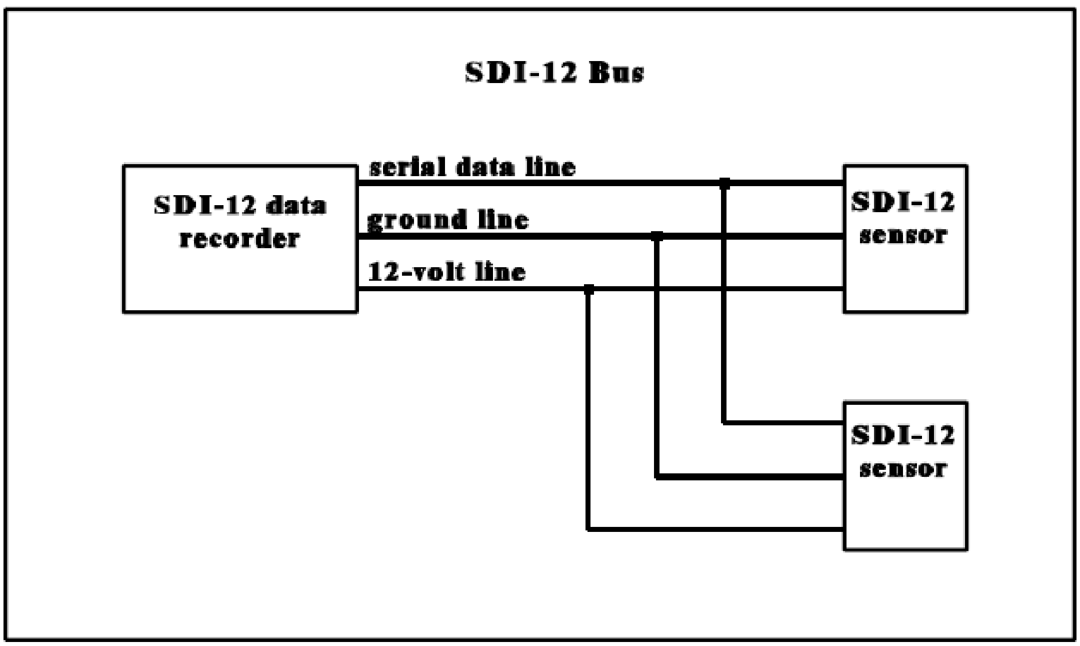

Figure 1. The SDI-12 Bus

All sensors must have a unique address. At most 62 sensors can be connected to a single bus.

Condition	Binary state	Voltage range
marking	1	-0.5 to 1.0 volts
spacing	0	3.5 to 5.5 volts
transition	undefined	1.0 to 3.5 volts

Table 1. Logic and voltage levels for serial data

1 start bit
7 data bits, least significant bit transmitted first
1 parity bit, even parity
1 stop bit

Table 2. SDI-12 byte frame format

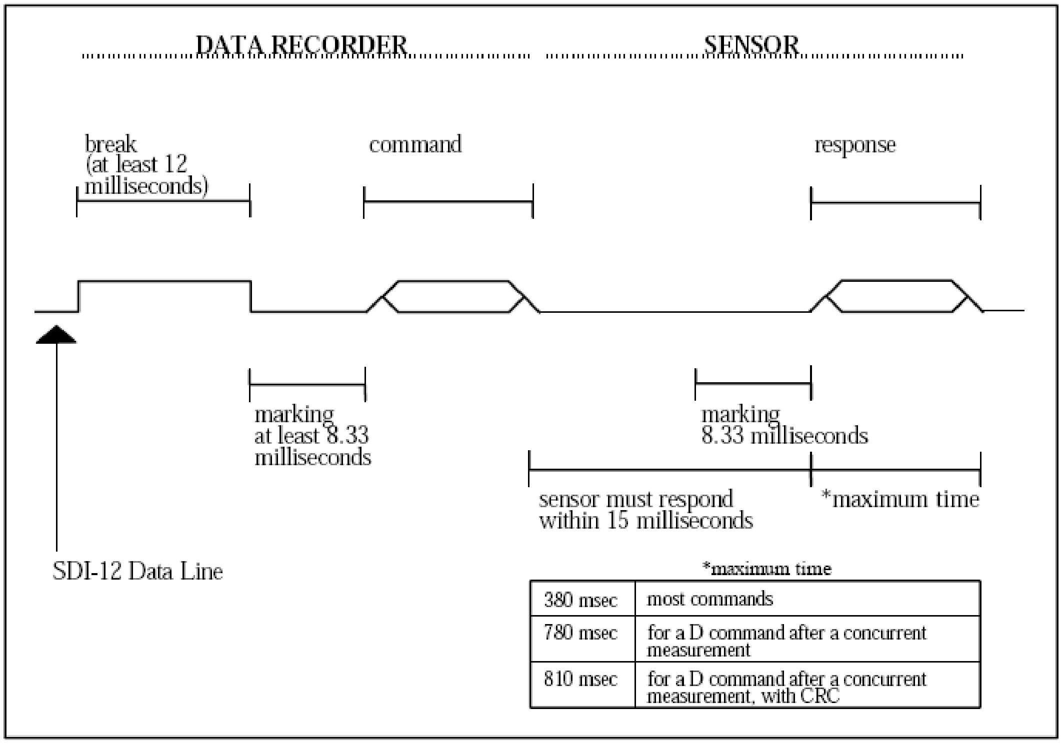

Figure 3. SDI-12 Timing