

SFS

Manual



Sap Flow Sensor *with SDI-12 Interface*

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CE Certification

This product is certified in accordance with the CE and UKCA requirements. A copy of the Declaration of Conformity can be downloaded from [ictinternational.com/ce](https://www.ictinternational.com/ce)

1 Product Overview

1.1 Introduction

The SFS Sap Flow Sensor precisely measures plant water use using Heat Ratio Method (HRM). Providing calculated sap velocities, the sensor can also provide raw needle temperature for post-processing.

Delivering six key metrics via SDI-12 v1.4, including sap flow rates and velocities, with low power consumption, and a rugged multi-probe design, it's built for long-term field use in agriculture, forestry, and ecology.

1.2 Product Specification

Voltage Input	9-24 V
Maximum Current at 12V	50 mA
Power Consumption	2.635 Wh/day
Minimum Measurement Interval	10 minutes (<i>recommended</i>)
Communication Interface	SDI-12
Measurement Accuracy	0.5 cm/hr
Measurement Resolution	0.01 cm/hr
Needle Options	12 mm, 22.5 mm and 35 mm
Enclosure Dimensions	150 x 100 x 75 mm (L x W x H)

Figure 1: Product Specification

1.3 Power States

Power States	Current Drawn (at 12V)
Charging	50 mA
Active	~ 4 mA
Sleeping	~ 2 mA

Table 1: SFS Power States

The Sap Flow Sensor (SFS) requires continuous power from the logger to operate correctly. Configure the logger so that the sensor always remains powered, even when the logger enters low-power modes.

2 What's in the box

2.1 Standard Inclusions

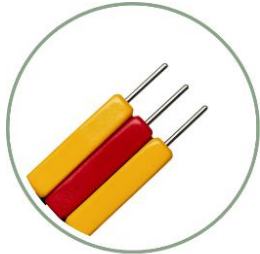
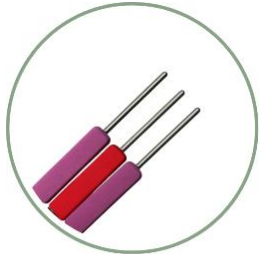


Inclusions	Sensor Model		
	SFS-12	SFS-22.5	SFS-35
Probe Set	 SF-12Set	 SF-22.5Set	 SF-35Set
Sensor Unit			
Sensor Cable	10 m (standard)		

Table 2: Standard Inclusions

2.2 Options

1. Extra Probe Sets – SF12Set/ SF22.5Set/ SF35Set
2. Test Block – SF-TB
3. Probe Extension Cables – 1m
4. Sensor Extension Cables – 1m/ 10m/ 20m

3 Operation and Measurement

3.1 Electrical Wiring



Figure 2: SFS Wiring Configuration

Input/Output	Wire Colours	Comment
Power	Red	Voltage Range: 9-24V
Ground	Black	
Data (SDI-12)	White	
RS485 (A)	Green	Firmware Upgrades Use Only
RS485 (B)	Blue	

Table 3: SFS Electrical Specification

3.2 Getting started

- Connect the sap-flow sensor to any SDI-12 v1.4-compatible data logger using the wiring in Figure 2.
- Send the address query *?!* to confirm the sensor is responding.
- Then request its identification string *al!* to verify the sensor’s model and serial number.

Once communication is confirmed, you can prepare the required SDI-12 program or script before installing the system in the field.

For guidance on writing logger programs and integrating the sensor with different platforms, please refer to the following documents:

Documentation	Description
Campbell Logger Guide	Instructions for configuring and programming Campbell Scientific data loggers for SDI-12 sensors.
Halytech Logger Guide	Setup and scripting guidance for using the sensor with Halytech loggers.
Campbell Scripts (GitHub)	Example SDI-12 scripts and templates for Campbell loggers, available in the project’s GitHub repository.

Table 4: Program Support

ICT International recommends bench testing the unit before installation.

3.2.1 Sensor Test

Place the probes in the optional test block to keep them steady. After the logger powers the sensor, open the logger's terminal so you can send SDI-12 commands. Run a manual measurement, wait for the sensor to signal that the reading is ready, and then retrieve the values. If the numbers look correctly formatted, stable, and sensible, the sensor is wired properly and ready for installation.

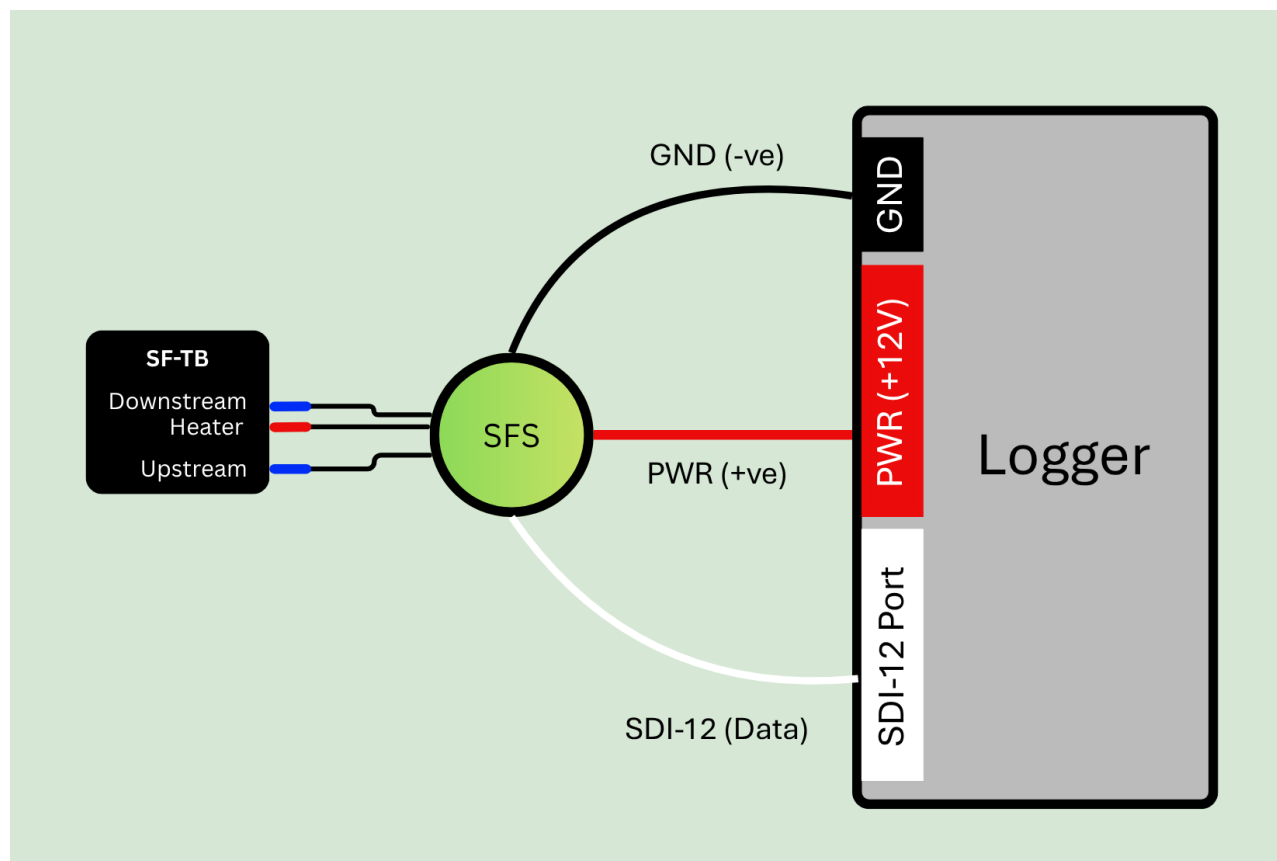


Figure 3: SFS Test Setup

Logger	Example SFS Response	Description
?!	0	Sensor Returns Address = 0
0I!	014ICT-INTLSFSMPC1.2Q1001	Sensor Information
0C!	015609	Logger must wait 156 seconds to get 9 results
0D0!	0+10.677+10.543	Uncorrected Outer and Inner Heat Pulse Velocities
0D1!	0+19.345+19.123	Corrected Outer and Inner Heat Pulse Velocities
0D2!	0+13.456+13.221	Corrected Sap Flow Velocities
0D3!	0+03.000+00.000	Needle Verification codes (section 5.4)
0D4!	0+00.000	Temperature Diagnostics (section 5.4)

Table 5: Test Example

4 SDI-12 Commands

4.1 Basic Commands

Command Name	Command	Description
Acknowledge Active	a!	Sensor active check
Send Identification	al!	Send identification information
Address Query	?!	Used when the address is unknown to have the sensor identify its address
Change Address	aAb!	Changes the address of the sensor from a to b
Start Measurement	aM! (Measurement Command) <i>383 seconds</i>	Tells the sensor to take a measurement
	aC! (Concurrent Command) <i>156 seconds</i>	Used to take a measurement when more than one sensor is used on the same data line
Send Data	aD0! (uncorrected outer and inner HPV)	Retrieves the data from a sensor
	aD1! (corrected outer and inner HPV)	
	aD2! (corrected outer and inner Sap Velocity)	
	aD3! (Heater and Thermistor Verification Code)	
	aD4! (Temperature Diagnostics)	
Baseline Temperature	aC1! <i>30 seconds average</i>	Performs Baseline Temperature Measurement
Trigger Heat Pulse	aC2! <i>10 seconds</i>	Performs a heat pulse
Raw Thermistor Data	aC3! <i>10 seconds</i>	Performs Raw Thermistor Data Measurement
Supercapacitor Voltage	aC4!	Performs Supercapacitor Voltage Check
Heater Voltage	aC5!	Performs Heater Voltage Check
Board Temperature	aC7!	Performs Board Temperature Check

Table 6: Basic SDI-12 Commands

4.2 Extended Commands

Command Name	Command	Description
Verification Command	aV!	Checks heater, thermistor and temperature rise diagnostics
High Volume Command	aHA! <i>143 seconds</i> • <i>10s ADC initialisation</i> • <i>3s heat pulse</i> • <i>130s MHRM heat pulse logging and calculation</i>	Sensor takes measurement and returns raw thermistor readings that followed the heat pulse. The total measurement time is 143 seconds
Configure Thermal Diffusivity	aXTD=<value>*	Change the thermal diffusivity. By default, it is set to 0.0025 cm/s
Configure Heater-to-measurement probe distance	aXHD=<value>!	Change the heater-to-measurement probe distance. By default, it is set to 0.5 cm
Configure Baseline Asymmetry Offset	aXBO=<value>!	Change the Baseline Asymmetry Offset. By default, it is set to 0 cm/hr
Configure Wound Diameter	aXWD=<value>!	Change the Wound Diameter. By default, it is set to 0.20 cm
Configure VS (i.e. Sap Velocity) Factor	aXVS=<value>!	Change the VS Factor. By default it is set to 0.64347

Table 7: Extended SDI12 Commands

4.3 SDI-12 Measurement Modes Comparison

Feature	Standard (M)	Concurrent (C)	High-Volume (H)
Measurement Behaviour	Sensor performs measurement immediately after receiving the command	Sensor begins measurement but releases the bus so other sensors can also measure	Sensor performs a measurement that produces a large dataset
Bus Usage	Bus is occupied until measurement time is returned	Bus is free during measurement; multiple sensors can measure simultaneously	Bus is occupied during data transfer due to large data size
Data Size	Small, fixed number of values	Small, fixed number of values	Large datasets (up to 999 values), ASCII or binary
Intended Use	Routine measurements; simple sensors	Multi-sensor networks; time-coordinated sampling	Sensors producing high-density or complex data

Table 8: SDI-12 Measurement Modes Comparison

5 Sensor configuration options

The SFS is a versatile unit that can be used with other SDI-12 sensors or in conjunction with other SFS (or a hybrid of these).

By default, the SFS is shipped with the address as 0, therefore it may be necessary to change the address configuration. When using multiple SFS sensors on a logger's SDI-12 port, start by connecting each sensor one at a time and assigning it a unique address (by default each SFS will have addresses set to "0"). This may be necessary with other sensors that are connected to the data logger as well to avoid clashes.

5.1 Using multiple sensors to measure the Soil, Plant and Atmosphere Continuum: Multi-Sensor Measurement Timing

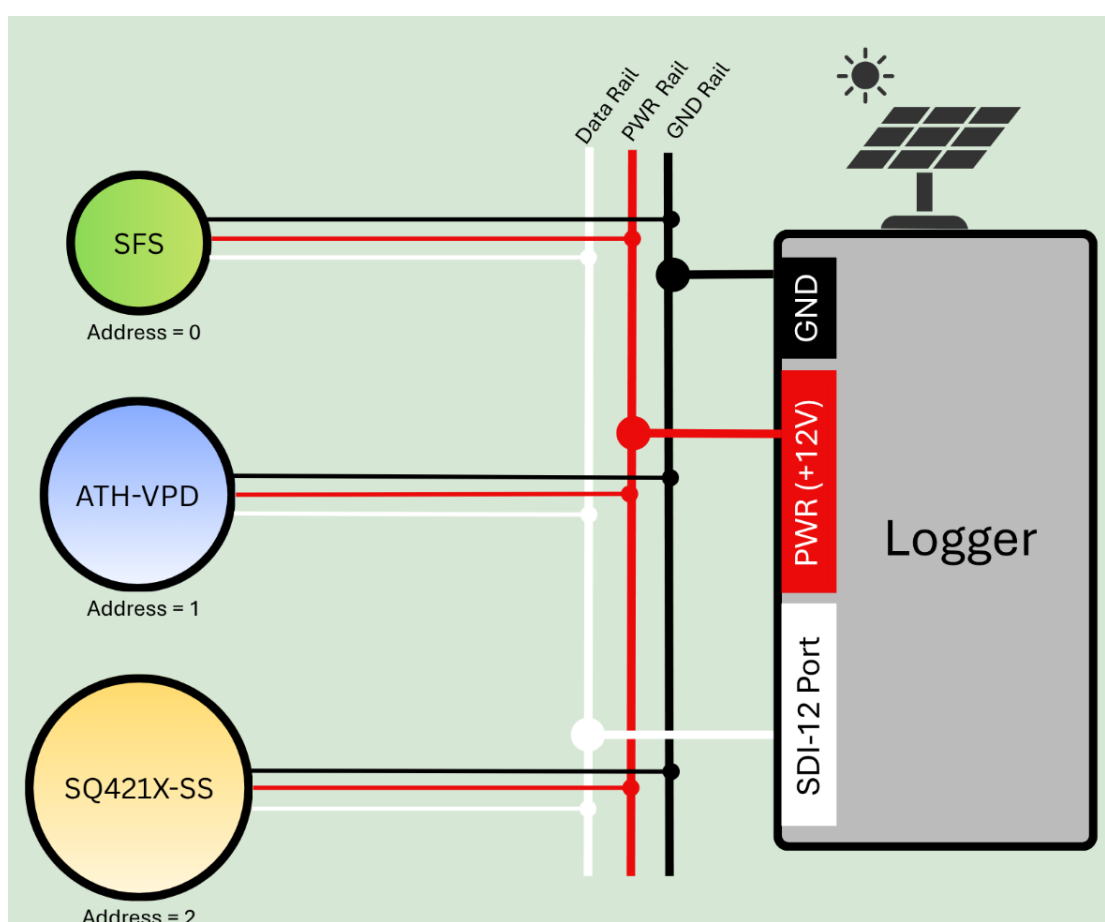


Figure 4: Multi-sensor setup

Measurement Timing and Sensor Coordination

When multiple SDI-12 sensors share the same measurement cycle, it is important that their measurement windows are aligned so the resulting dataset represents a single, coherent point in time. In this system, the SFS sap flow sensor has the longest measurement duration, while the ATH-VPD and SQ421-SS complete their measurements within only a few seconds. For this reason, the SFS must always be triggered first.

1. SFS Measurement (Address 0)

The SFS begins its measurement at the start of the cycle. A full SFS measurement requires approximately 156 seconds to complete. During this period, the sensor performs ADC initialization, heating, and internal processing. No other sensors should be triggered until the SFS measurement window has finished.

2. ATH-VPD Measurement (Address 1)

Once the SFS measurement has completed, the ATH-VPD sensor can be triggered. This sensor requires only a few seconds to return valid data. Its measurement window should be scheduled immediately after the SFS window so that its data represent the same environmental conditions at the end of the SFS cycle.

3. SQ421-SS Measurement (Address 2)

The SQ421-SS PAR sensor also completes its measurement within a few seconds. It should be triggered directly after the ATH-VPD, ensuring that all fast-responding sensors capture conditions at nearly the same moment.

Example Timing Sequence:

If a measurement cycle begins at 10:00:00 a.m.:

- SFS completes its measurement at approximately 10:02:36 a.m.
- ATH-VPD completes its measurement a few seconds later
- SQ421-SS completes shortly after the ATH-VPD

Because the fast sensors are triggered immediately after the SFS measurement window, all three sensors effectively represent a common measurement time of approximately 10:03 a.m.

This sequencing ensures that all sensor outputs are aligned to the same physical moment, providing consistent and synchronised data for analysis.

5.2 Using multiple SFS sensors

Depending on how the SFS is connected to the datalogger there are different approaches to the measuring multiple SFS.

- If wired on a single port (e.g. bussed) then it is necessary to use the concurrent command
- If each SFS is connected to an individual port, then they can be measured using the standard measurement command.

5.2.1 Concurrent Measurement

Set up the program in the logger so it sends the *aC!* command to each sensor in sequence. Include a 156-second delay to allow all measurements to finish. After that,

poll each sensor using the *aD0!*, *aD1!*, and *aD2!* commands. Once the data is returned, save it to the logger's internal memory or an external memory card.

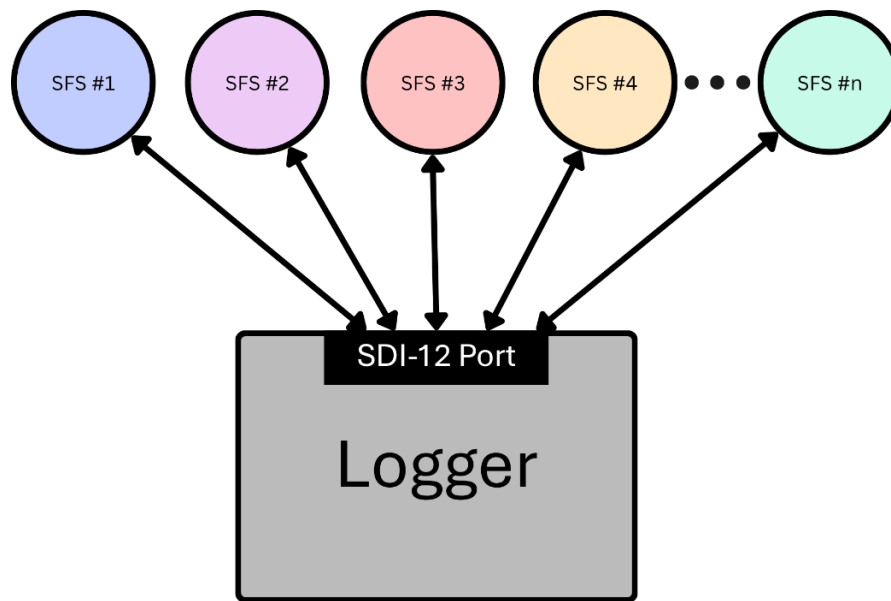


Figure 5: Concurrent Example

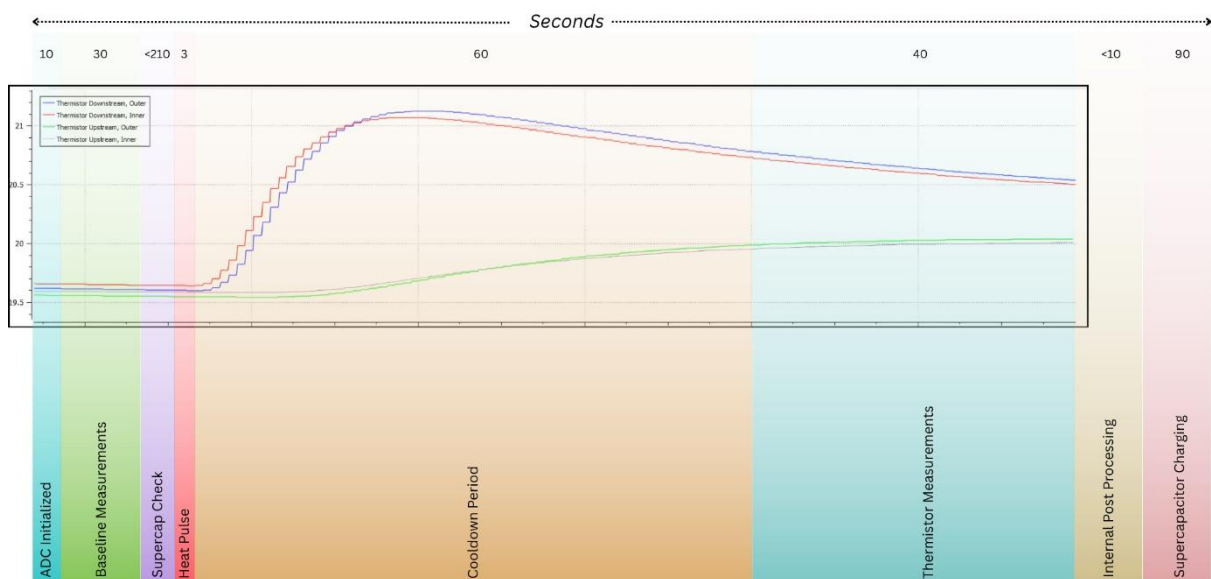


Figure 6: HRM Measurement Cycle

Note, a Concurrent HRM command variant (e.g. *aC!*) will abort if it exceeds 156 seconds. Hence the supercapacitors must be fully charged before initiating the command. A Standard HRM command variant (e.g. *aM!*) is 383 seconds to ensure that even a fully depleted supercapacitor bank will charge before a measurement, and the measurement will complete.

5.2.2 Standard Measurement

Using the standard *aM!* measurement command, the logger will trigger each sensor one at a time. SDI-12 does not allow multiple sensors to run M! measurements concurrently on the same bus, so each sensor must complete its full measurement cycle before the next one is started.

An SFS requires up to 383 seconds to complete a measurement command, including the time needed to recharge its supercapacitor bank. Because each sensor must finish before the next can begin, the total measurement time increases with every additional sensor. For example, six sensors would require more than 38 minutes to complete a full sequence, which makes this approach unsuitable for applications with tight timing requirements or frequent sampling intervals.

After each sensor completes its measurement, the logger can retrieve the results using *aD0!*, *aD1!*, and *aD2!*, and then store the returned values in internal or external memory.

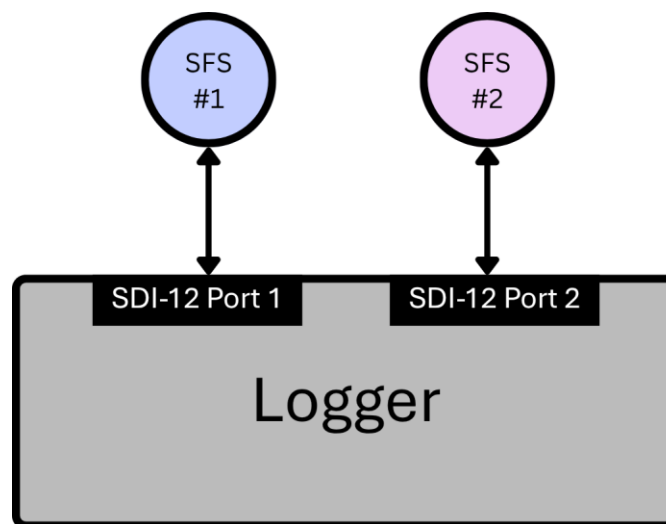


Figure 7: Sensor Logger Setup (for *aM!* command)

Note: Use the Measurement command when your sensor logger setup includes two or more SDI-12 ports, with each SFS connected to a separate SDI-12 ports. This command is especially helpful when:

- *The logger cannot add delays between measurements, and*
- *The logger's power is only active during measurement.*

In these situations, the Measurement command ensures that every SFS on each SDI-12 port can take a reading and properly charge its supercapacitor bank.

5.3 High Volume Measurement for research purposes

The *OHA!* command asks the sensor at address 0 to begin a High-Volume ASCII measurement. When the sensor receives this command, it immediately replies with a short status message—for example: 0143480.

This response contains three pieces of information:

- Sensor address: 0
- Time remaining until the full dataset is ready: 143 seconds
- Total number of data points that will be available: 480 values

These 480 values are temperature readings collected once per second from four thermistor channels. The data is arranged in repeating groups of four:

1. Thermistor 1 OUT – every $4n^{\text{th}}$ value (*blue*)
2. Thermistor 1 IN – every $(4n + 1)$ value (*green*)
3. Thermistor 2 OUT – every $(4n + 2)$ value (*orange*)
4. Thermistor 2 IN – every $(4n + 3)$ value (*pink*)

Command	Value 1	Value 2	Value 3	Value 4	Value 5	Value 6	Value 7	Value 8	Value 9	Value 10
<i>OD0!</i>	+11.768	+14.933	+13.546	+12.314	+15.879	+14.321	+13.278	+11.624	+15.451	+13.062
<i>OD1!</i>	+13.921	+12.678	+14.873	+13.547	+11.876	+15.324	+12.987	+15.634	+13.987	+12.784
<i>OD2!</i>	+11.768	+14.933	+13.546	+12.314	+15.879	+14.321	+13.278	+11.624	+15.451	+13.062
<i>OD3!</i>	+19.929	+18.658	+17.413	+18.545	+17.869	+18.724	+19.937	+16.998	+17.316	+17.354
<i>etc.</i>										

Table 9: Raw Data Visualization

Each index in the dataset corresponds to the number of seconds that have passed since the heat pulse began. Once this sequence finishes, the complete set of thermistor readings is ready to be retrieved.

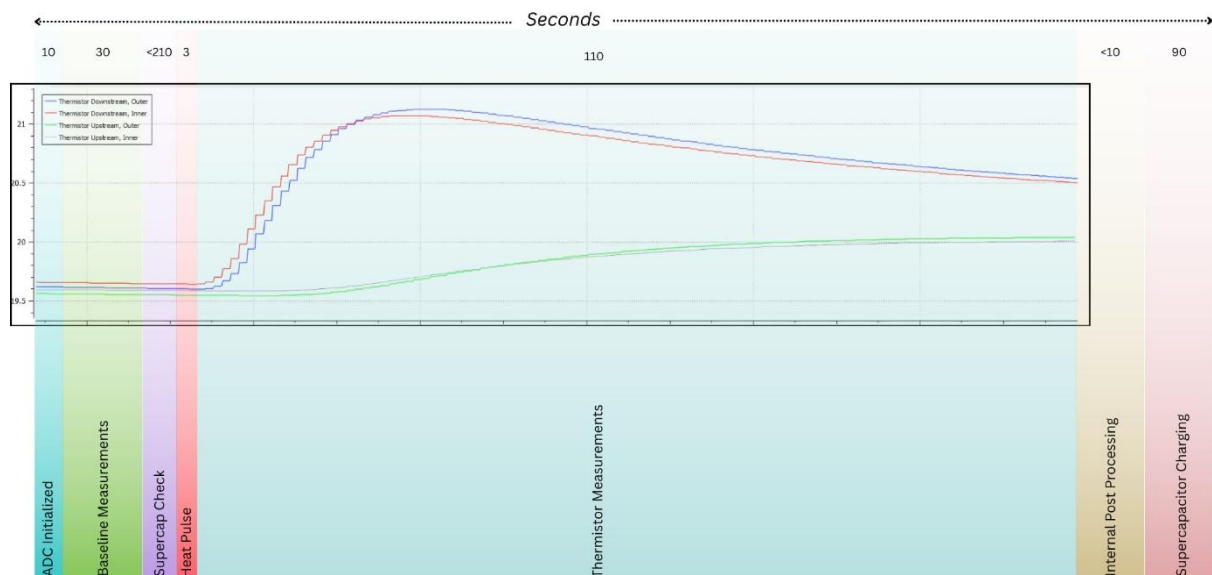


Figure 8: Raw Data

Note, a High-Volume raw data (*aHA!*) command will abort if it exceeds 143 seconds. Hence the supercapacitors must be fully charged before initiating the command.

6 Maintenance and Support

6.1 Serial Number Identification

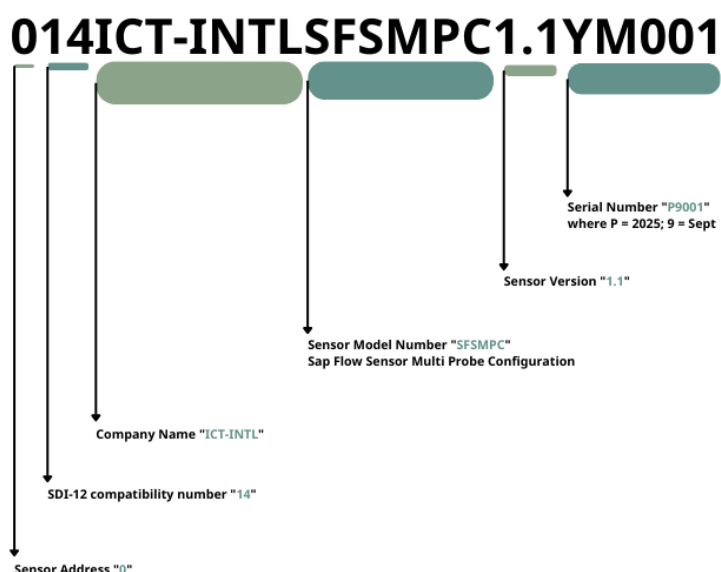


Figure 9: Serial Number Identification

6.2 Firmware Upgrade

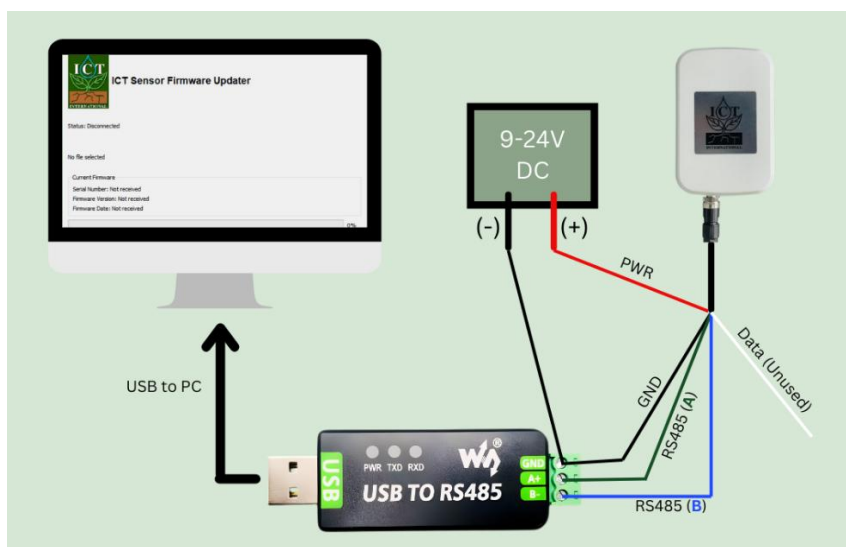


Figure 10: SFS Firmware Update Process

For the SFS firmware update process the following tools are required:

1. Industrial USB to RS485 Converter - <https://www.waveshare.com/product/usb-to-rs485.htm>
2. DC Power Source 9-24V Rated
3. ICT Sensor Firmware Updater v1.1.0 – provided by ICT International
4. Latest Sap Flow Sensor Firmware (.sfs) file – provided by ICT International

After wiring the sensor as shown in Figure 5.1, launch the ICT Sensor Firmware Updater on a Windows PC running Windows 10 or later.

1. Click the “Select File” button on the software and open the latest firmware .sfs file from file explorer

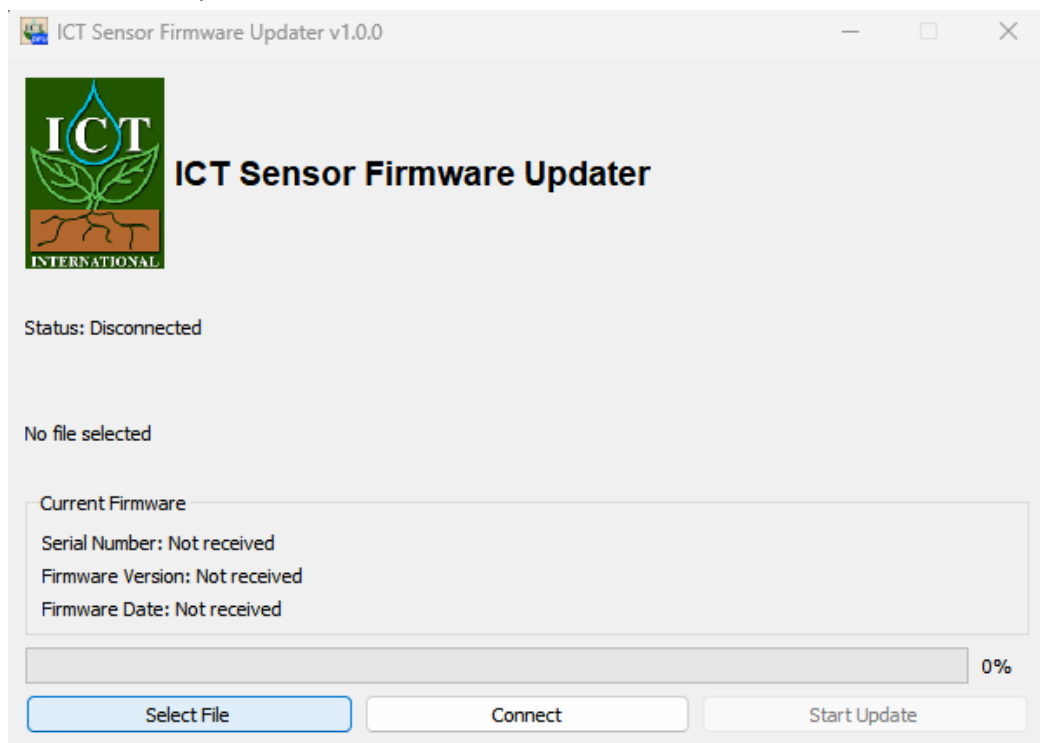


Figure 11: Select the firmware file

2. Click the “Connect” button on the software

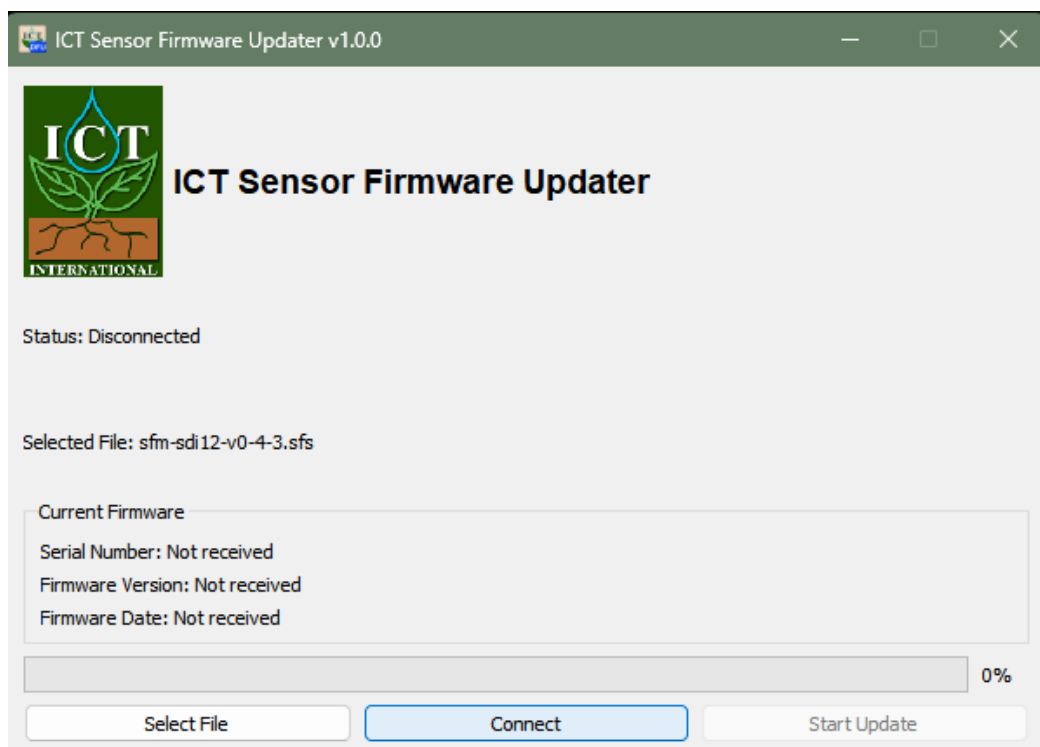


Figure 12: Connect the sensor

3. Once connected the Current Firmware section of the software will populate with the current firmware version of the sensor, click “Start Update”

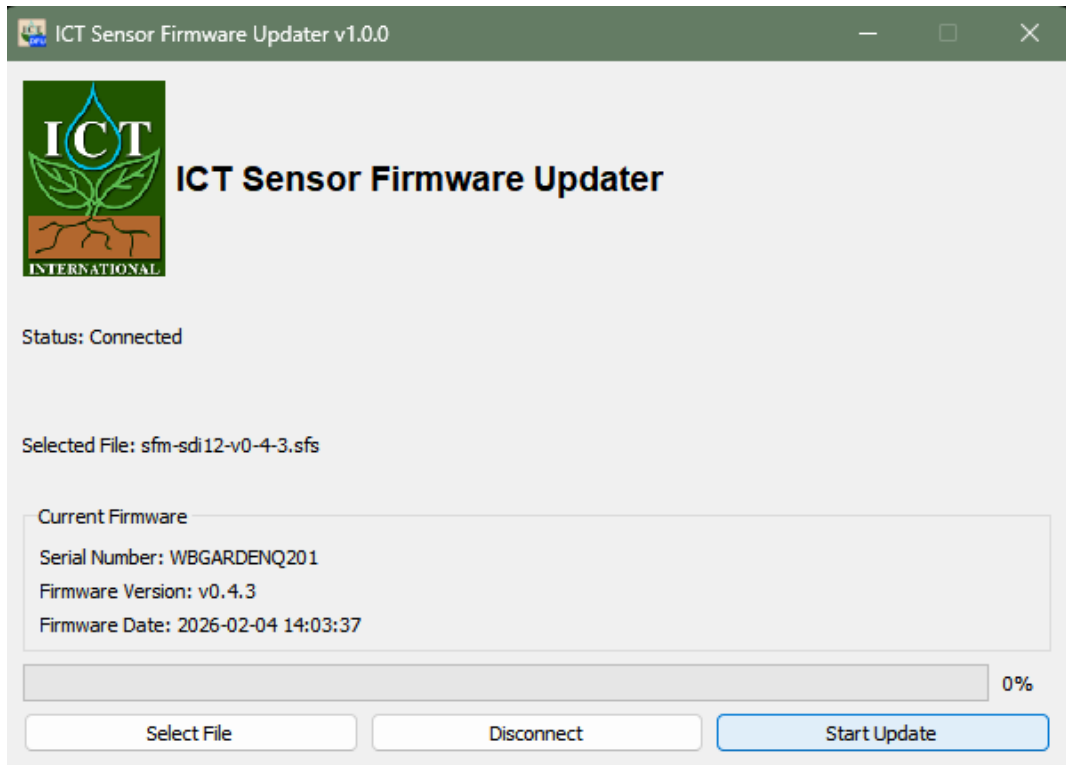


Figure 13: Start Update process

4. Once the “Status” of the software changes to “Done”, click “Disconnect”

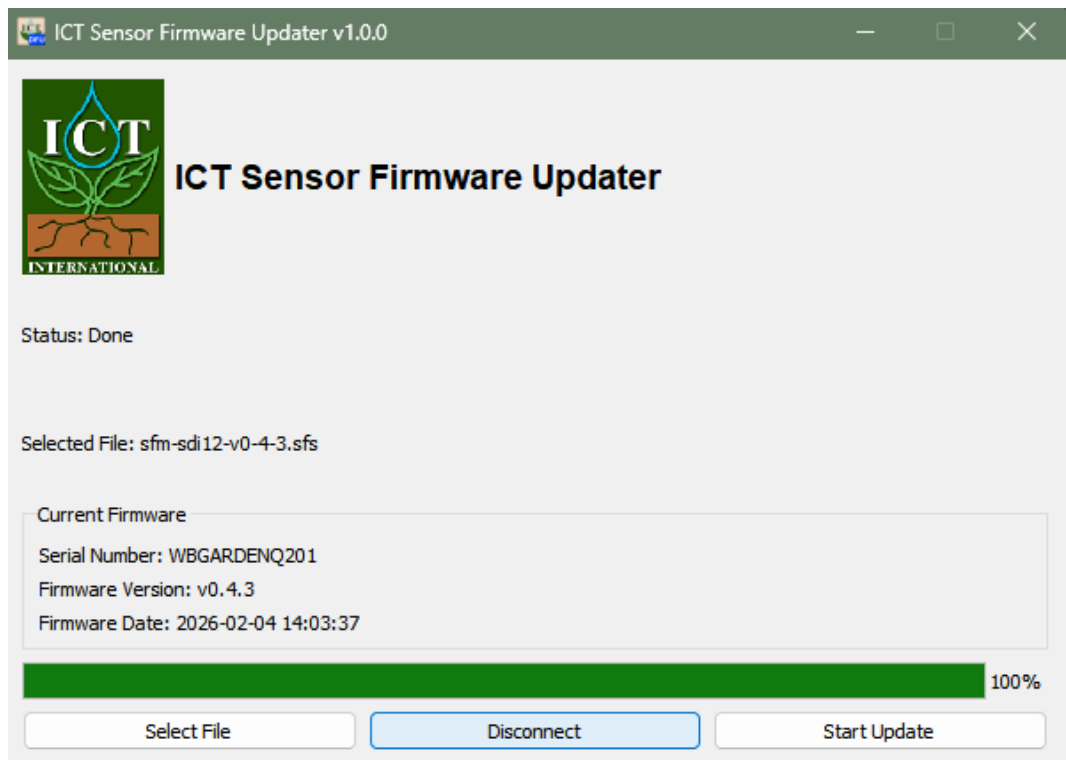


Figure 14: Disconnect the sensor from the software

5. Switch off the power supply before unplugging the sensor

Note: the sensor is shipped with the latest firmware available when manufactured – use the Serial number to check date of Manufacture against FW release history on GitHub.

6.3 Customer Repairs

Connectors	ICT P/N	Supplier P/N	Supplier Name
Thermistor Probes	Connect-F	1441066	Phoenix Contact
Heater Probe	Connect-M	1441024	
Data Cable	DataConnect-C	1424649	

Table 10: Customer Repair Parts

6.4 Diagnostic Commands

6.4.1 Heater Diagnostics Codes

Value	Shorthand	Meaning
-2	Heater Needle Determined	This is the default code for a sensor that has not yet run a heat pulse.
-1	Determination Error	Caused by an inability to detect a stable heat pulse.
0	Needle Short Error	A possible short has occurred or needle resistance is very low.
1	35mm Heater Detected	The 18 ohm, 35mm heater needle has been detected.
2	12mm Heater Detected	The 8 ohm, 12 mm heater needle has been detected.
3	22.5mm Heater Detected	The 13 ohm 25.3mm heater needle has been detected.
4	Open Circuit Error	Likely no needle attached / poor connection made. Reconnect needle.

Table 11: Heater Diagnostics Code

6.4.2 Thermistor Diagnostics Codes

Value	Meaning	Suggested Action
-1	Thermistors undetermined	This is the default code for a sensor that has not yet run measurement that uses the ADC.
0	All Thermistors valid	None
1	Downstream probe partially disconnected or broken.	Reconnect the downstream thermistor probe.
2	Downstream probe partially disconnected or broken.	Reconnect the downstream thermistor probe.
3	Downstream probe fully disconnected or broken.	Reconnect the downstream thermistor probe.
4	Upstream probe partially disconnected or broken.	Reconnect the upstream thermistor probe.
5	Upstream and downstream probes partially disconnected or broken.	Reconnect both thermistor probes.
6	Upstream and downstream probes partially disconnected or broken.	Reconnect both thermistor probes.
7	Downstream probe fully and upstream probe partially disconnected or broken.	Reconnect both thermistor probes.
8	Upstream probe partially disconnected or broken.	Reconnect the upstream thermistor probe.
9	Upstream and downstream probes partially disconnected or broken.	Reconnect both thermistor probes.
10	Upstream and downstream probes partially disconnected or broken.	Reconnect both thermistor probes.
11	Downstream probe fully and upstream probe partially disconnected or broken.	Reconnect both thermistor probes.
12	Upstream probe fully disconnected or broken.	Reconnect the upstream thermistor probe.
13	Upstream probe fully and downstream probe partially disconnected or broken.	Reconnect both thermistor probes.
14	Upstream probe fully and downstream probe partially disconnected or broken.	Reconnect both thermistor probes.
15	Upstream and downstream probes fully disconnected or broken.	Reconnect both thermistor probes.

Table 12: Thermistor Diagnostics Codes

6.4.3 Temperature Rise Diagnostics Codes

Value	Meaning
0	Temperature Rise OK
1	TDIN ERROR
2	TDOUT ERROR
3	TDIN + TDOUT ERROR
4	TUIN ERROR
5	TUIN +TDIN ERROR
6	TUIN + TUOUT ERROR
7	TUIN + TDIN + TDOUT ERROR
8	TUOUT ERROR
9	TUOUT + TDIN ERROR
10	TUOUT + TDOUT ERROR
11	TUOUT + TDIN + TDOUT ERROR
12	TUOUT + TUIN ERROR
13	TUOUT + TUIN + TDIN ERROR
14	TUOUT + TUIN + TDOUT ERROR
15	TUOUT + TUIN + TDIN + TDOUT ERROR

Table 13: Temperature Rise Diagnostics Codes

6.5 Detailed Power Information

6.5.1 SFS Power States

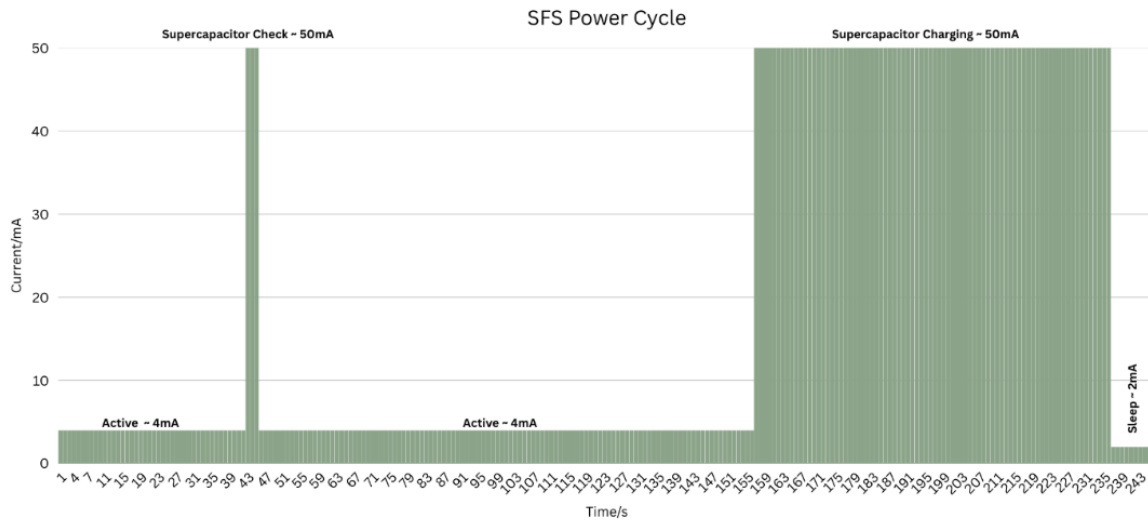


Figure 15: SFS Power Cycle Graph

SFS States	Description (10-minute Measurement Cycle)
Active	<i>ADC Initialization & Baseline Temperature Measurements (1–42 seconds)</i> The sensor powers up its ADC, stabilizes internal electronics, and records baseline temperature values used for HRM calculations.
Charging	<i>Supercapacitor Check & Top-Up (43–45 seconds)</i> The system checks the supercapacitor voltage and adds a small top-up charge if required. This ensures the capacitor has enough stored energy for the upcoming measurement phase.
Active	<i>Measurement, Processing & HRM Calculation (46–156 seconds)</i> The sensor performs the full Heat Ratio Method measurement, processes raw thermal data, and calculates sap flow outputs. This is the highest-power phase of the cycle.
Charging	<i>Supercapacitor Charging Cycle (157–236 seconds)</i> The supercapacitor is fully recharged from the SDI-12 supply. This prepares the sensor for the next measurement cycle and prevents SDI-12 current overload.
Sleeping	<i>Sleep (237–600 seconds)</i> The sensor enters deep sleep, drawing minimal current. Only essential circuitry remains active until the next cycle begins.

Table 14: SFS States

6.5.2 SFS Power Consumption

Power States	Active	Supercapacitor Check	Active	Supercapacitor Charging	Sleep
Time (s)	1-42	43-45	46-156	157-236	237-600
Q ₁	0.0467				
Q ₂		0.0417			
Q ₃			0.1233		
Q ₄				1.1111	
Q ₅					0.2022
Q _T	1.525 mAh for a 10-minute cycle at 12V				
Power (Wh/day)	2.635 Wh/day for a 10-minute cycle at 12V				

Table 15: SFS Power Consumption at 12V input

The current draw of the sensor differs depending on the input voltage and device state. Empirically measured data on a SFS gave the following results:

Input (V)	Current when charging supercapacitors (mA)	Current when sensor idle (mA)	Current when sensor asleep (mA)
9	67.5	3.66	1.84
12	50	2.96	1.57
15	41	2.57	1.40
18	35	2.30	1.30
21	31	2.11	1.22
24	28	1.96	1.15

Table 16: SFS Current Draw at different input voltages

With a 15-minute measurement interval, using a high-volume measurement command, power consumption can be deduced for a 24hr duration.

Input (V)	Charging power per measurement (Wh)	Active power per measurement (Wh)	Sleep power per measurement (Wh)	Power per day (Wh)
9	0.0206	0.0014	0.0029	2.39
12	0.0203	0.0015	0.0033	2.41
15	0.0208	0.0016	0.0036	2.51
18	0.0214	0.0018	0.0041	2.61
21	0.0221	0.0019	0.0044	2.73
24	0.0228	0.0020	0.0048	2.84

Table 17: SFS Power Draw for high volume command

7 Additional Information

7.1 Interchangeable Heater and Thermistor Probes

The heater and thermistor probes are designed to be removable, allowing the sensor to be used across different plant species. Probes can be swapped while the sensor is powered off, and no software adjustments are required. An internal hardware circuit automatically supplies the correct heating energy for the installed heater needle, and the firmware detects which heater is connected. The attached heater needle code is returned as the 7th value in a Heat Ratio Method (HRM) Measurement command but can be more efficiently diagnosed with a Trigger Heat Pulse command (*aC2!*). The attached thermistor needle diagnostics are similarly returned as the 8th value in a Heat Ratio Method (HRM) Measurement command but can be more efficiently diagnosed with a Raw Thermistor Data command (*aC3!*).

The SFS offers three needle lengths:

- 35 mm – *suitable for woody stems*
- 22.5 mm – *suitable for both woody and herbaceous stems*
- 12 mm – *suitable for herbaceous stems with diameters up to 10 mm*

These probes, along with their corresponding heaters, are equipped with M8 connectors.

Note: ICT International offers three standard needle sets. Customers can request custom thermistor positions by printing the HRM Needle Design.pdf and aligning it with the desired sapwood profile.

7.2 Supercapacitor Bank

The supercapacitor bank is used to store energy for heat pulses. The supercapacitors allow up to 6x SFS devices to be supported on the SDI-12 bus without special power considerations i.e. no need for complicated software management of power or breaking of protocol power standards. The supercapacitors nominally charge to 4.8V. They can be diagnosed with a Supercapacitor Voltage command.

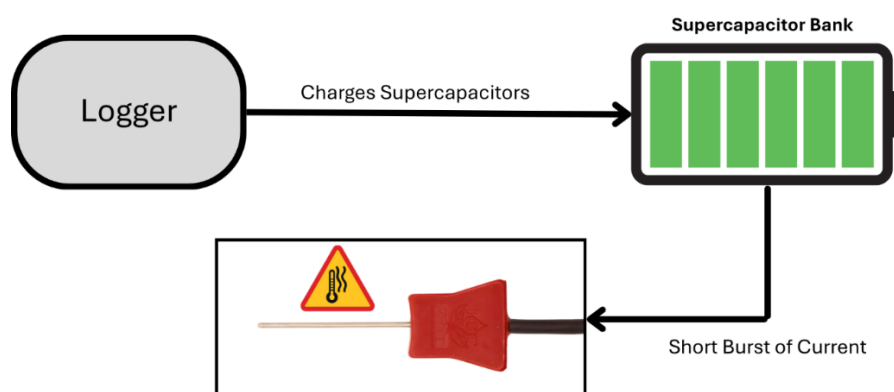


Figure 16: Needle Types

7.3 Heater Power Management

A key component of a reliable sap flow sensor is a circuitry that maintains stable and predetermined current flowing through the heater needle. In the SFS, all heater types are driven with a constant current of 0.67 A. The voltage automatically adjusts based on heater resistance:

- 35 mm (18 Ω): 12.06 V
- 12 mm (8 Ω): 5.36 V
- 22.5 mm (13 Ω): 8.71 V

This results in much more consistent power per millimeter across all heater types which is roughly 0.263 W/mm.

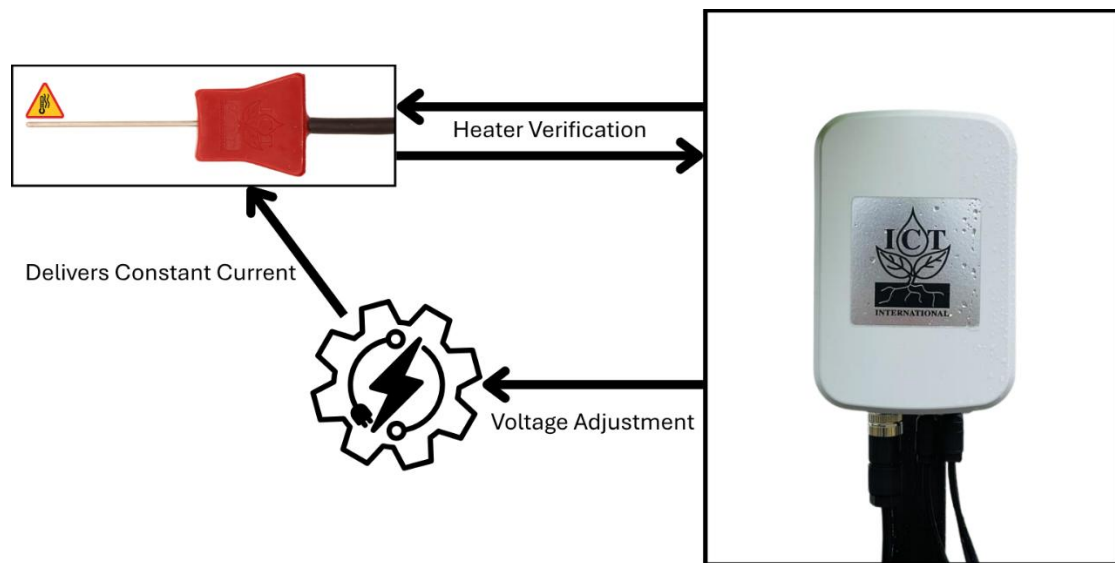


Figure 17: Heater Power Management

8 Appendix

8.1 Enclosure Connector Layout

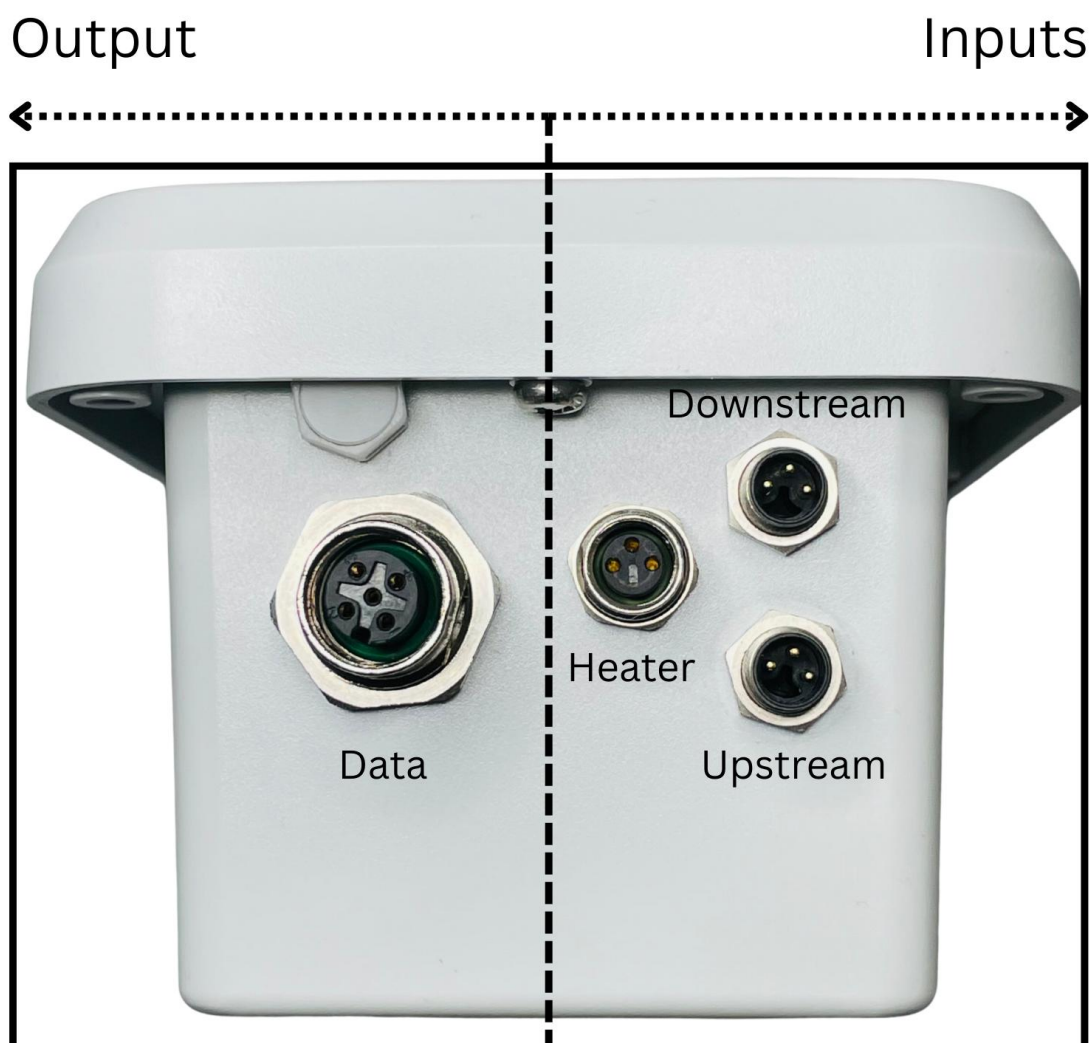


Figure 18: SFS Connector Layout

This diagram shows where each cable connects on the Sap Flow Sensor (SFS). The Data port on the left sends measurements out to the logger, while the three ports on the right are inputs from the probe: Heater (middle connector) powers the constant current heater, and Upstream and Downstream (top and bottom connectors) connect to the two thermistor probes inserted above and below the heater.

8.2 Heater Probe Connector Wiring

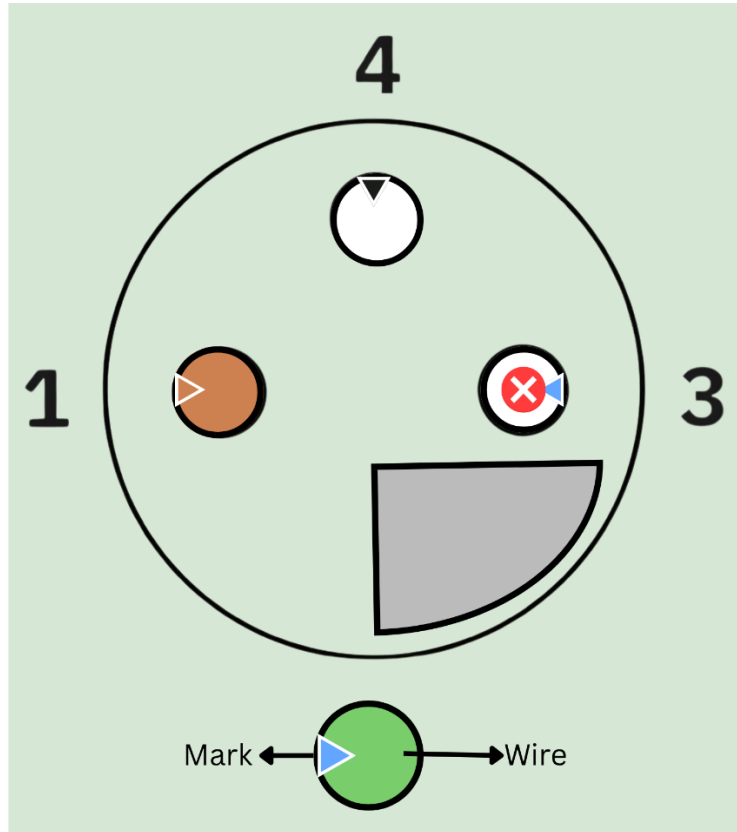


Figure 19: Heater Probe Connector Wiring

8.3 Thermistor Probe Connector Wiring

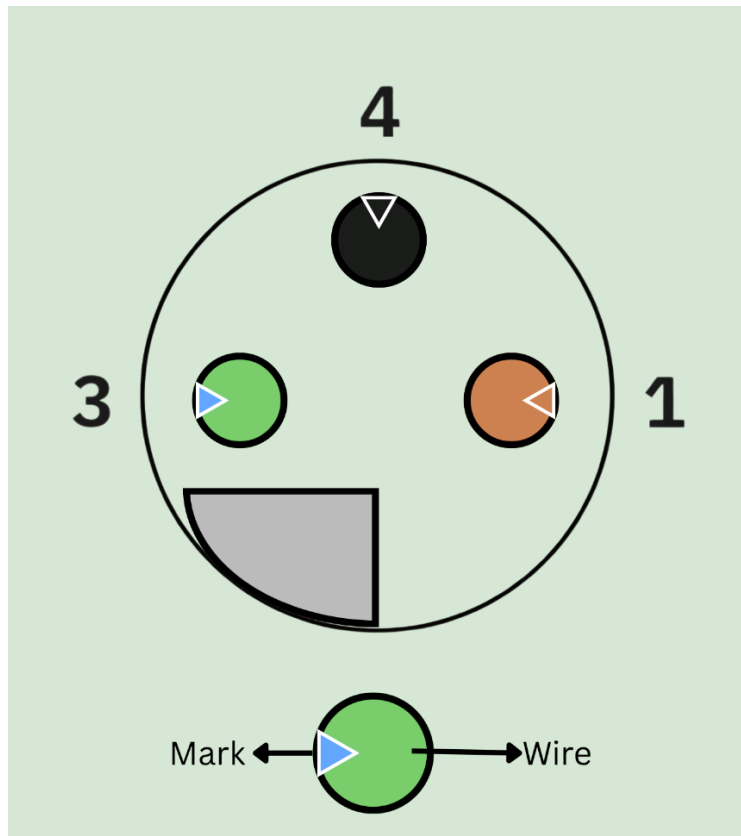


Figure 20: Thermistor Probe Connector Wiring

8.4 Cable Connector Wiring

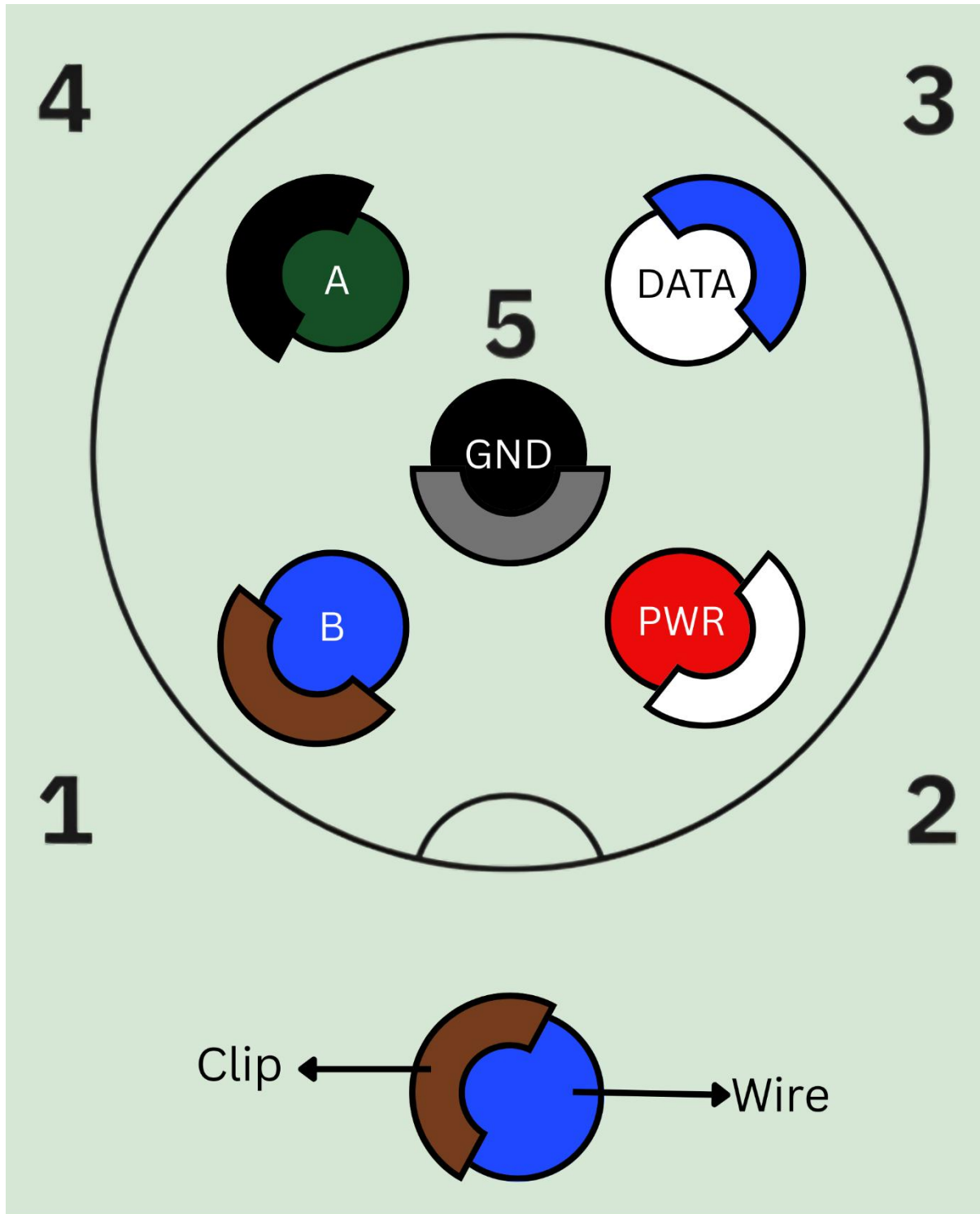


Figure 21: SFS Cable Connector Wiring

