Implexx Sap Flow Sensor Gen 2

IX-SF60-G2

Manual

ver. July 2025

Implexx
Digital Environmental Sensing

WARNING!

Opening of the white enclosure will damage the sensor and void warranty. Under no circumstances should the white enclosure ever need to be opened or be opened.

WARNING!

Only ever start a measurement of the Sap Flow Sensor when the needles, or probes, are embedded inside a material such as the foam block or a tree. **NEVER** start a measurement when the needles are in air. This may cause damage to the heater element and void warranty.

WARNING!

The most frequent data collect interval is 10 minutes. An SDI-12 M! or C! command should never be sent to the sap flow sensor more frequently than 10-minute intervals.

WARNING!

Only a 12 VDC power should be applied to the Implexx Sap Flow Sensor Gen 2. The application of a larger VDC power supply may damage the sensor and will void warranty.

WATCH THE YOUTUBE INSTALLATION VIDEO!

There is a brief, YouTube video demonstrating the installation of the Implexx Sap Flow Sensor Gen 2.

We strongly recommend you watch the video now:

IX-SF60-G2 Model: https://www.youtube.com/watch?v=TxYqI1C2wWc

IX-SF30-G2 Model: https://www.youtube.com/watch?v=QJXdQWPkfeE

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Disclaimer and Warranty

Warranty is immediately void if the white enclosure is opened or if there is an attempt to open the white enclosure.

Seller warrants new equipment of its own manufacture against defective workmanship and materials for a period of one year from the date of receipt of equipment.

Note: We do not consider the results of ordinary wear and tear, neglect, misuse, or accident as defects.

The Seller's liability for defective parts shall in no event exceed the furnishing of replacement parts \freight on board the factory where originally manufactured. Material and equipment covered hereby which is not manufactured by Seller shall be covered only by the warranty of its manufacturer. Seller shall not be liable to Buyer for loss, damage or injuries to persons (including death), or to property or things of whatsoever kind (including, but not without limitation, loss of anticipated profits), occasioned by or arising out of the installation, operation, use, misuse, non-use, repair, or replacement of said material and equipment, or out of the use of any method or process for which the same may be employed. The use of this equipment constitutes Buyer's acceptance of the terms set forth in this warranty.

There are no understandings, representations, or warranties of any kind, express, implied, statutory or otherwise (including, but without limitation, the implied warranties of merchantability and fitness for a particular purpose), not expressly set forth herein.

Introduction

The Implexx Sap Flow Sensor Gen 2 enables the latest advancements in the measurement of plant water use for researchers, growers, engineers and students.

There are two models of the Implexx Sap Flow Sensor Gen 2 (Figure 1):

- IX-SF30-G2: a 30 mm long sensor with two measurement points.
- IX-SF60-G2: a 60 mm long sensor with five measurement points.

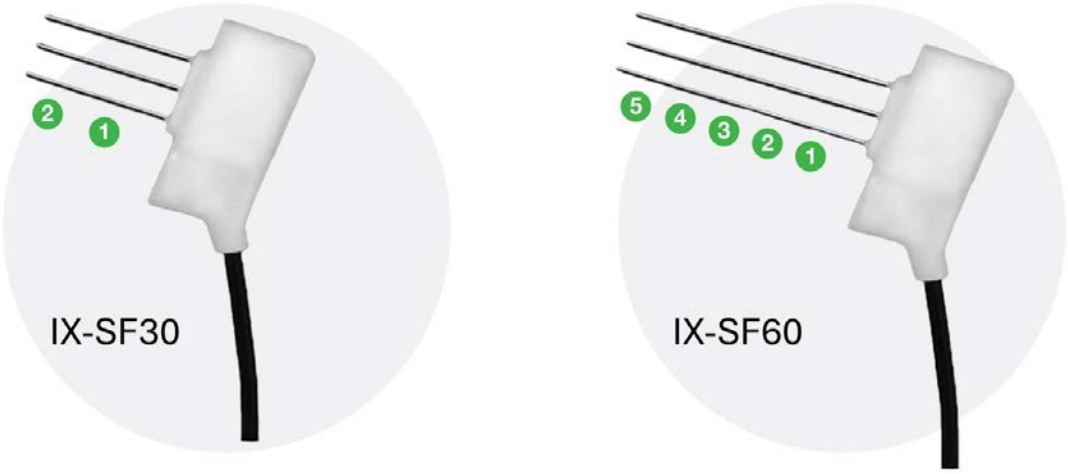

Figure 1. The two models of the Implexx Sap Flow Sensor Gen 2: IX-SF30 and IX-SF60.

Aside from the length of the needles, and the number of measurement points, the two models are the same. That is, both models estimate sap flux density, and stem water content, based on the same theory and measurement principles (outlined further in this manual).

The Implexx Sap Flow Sensor Gen 2 outputs many parameters including:

- Total stem or trunk sap flow

- Sap flux density

- Raw data for the calculation of heat velocity and sap flux density

- Sapwood, or stem, water content

- Sapwood, or stem, temperature

- Sapwood, or stem, thermal properties

- Electronic and sensor diagnostics.

Most users will only require total sap flow or sap flux density. But it is strongly recommended to always log and monitor the raw data required for the calculation of sap flow.

The Implexx Sap Flow Sensor Gen 2 utilises the SDI-12 protocol for integration into data logging, IoT and telemetry systems. User must have an SDI-12 enabled device and it is assumed that users have some familiarity with the SDI-12 protocol. Implexx Sense can provide programs and programming advice for some models of data loggers or IoT device, if required.

This manual outlines the installation and wiring procedure for the Implexx Sap Flow Sensor Gen 2. The manual contains information for both models: IX-SF30-G2 and IX-SF60-G2.

Maintenance and troubleshooting of common issues are also outlined in this manual. The published, scientific theory, on which the sensor measurements are based, are provided. Lastly, references and citations are provided.

Specifications – IX-SF60-G2 Model

Feature	Specification
Sap Flow Measurements	
Measurement Range	-200 to >+1000 cm/hr heat velocity
Measurement Error	< 3% or ±0.1 cm/hr heat velocity
Measurement Resolution	0.001 cm/hr heat velocity
Measurement Points	IX-SF60-G2: 5
Measurement Theory	Dual Method Approach, Heat Ratio (Slow Rates of Flow Method), Tmax
Stem Water Content Measurements	
Measurement Range	0 to 100 % volumetric
Measurement Error	±3%
Measurement Resolution	0.01
Measurement Points	IX-SF60-G2: 5 (downstream direction)
Stem Temperature Measurements	
Measurement Range	-30 to +70 °C
Measurement Error	±0.015 °C
Measurement Resolution	0.001 °C
Measurement Points	IX-SF60-G2: 10 (downstream and upstream)
Sensor Specifications	
Response Time	200 milliseconds
Power Input	12 VDC
Power Consumption	IX-SF60-G2: Idle: 4mA; Measure: 520 mA
Sensor Output	SDI-12 (ver. 1.4)
Measurement Duration	124 seconds
Environmental Rating	IP68; -20 to +70 °C
Needle Dimensions	IX-SF60-G2: L: 60 mm; D: 1.8 mm
Enclosure Dimensions	H: 50 mm; W: 25 mm; D: 11 mm
Enclosure Materials	Acrylonitrile Styrene Acrylate
Needle Materials	Stainless Steel (304)
Cable Materials	Ozone, UV and weather-resistant according to EN 50396 and HD 605 S2
Cable Length	5 m (standard); 50 m (maximum)
Warranty	1 year parts and labour

Sensor Design Overview

The Implexx Sap Flow Sensor consists of a white enclosure and 3 stainless steel probes set approximately 8 mm apart and in parallel.

The white enclosure houses the electronics of the sap flow sensor. Opening of the white enclosure will likely damage the electronics and void warranty.

The stainless steel probes are the temperature sensors and heater element. The top and bottom probes measure temperature whereas the central probe is the heater element.

The top probe is also referred to as the downstream temperature probe and the bottom probe the upstream temperature probe. Downstream and upstream refer to the direction of sap flow in the plant. Usually, sap in xylem flows from the roots, through the stem and towards the leaves in the canopy. This pathway of flowing sap is analogous to water running in a river from the mountains to the ocean. The mountains are upstream, and the ocean is downstream to the point of measurement. Similarly, the roots are upstream, and the canopy is downstream to the point of sap flow measurement. Therefore, the top and bottom temperature probes are commonly referred to as the downstream and upstream temperature probes.

There are five thermistors located within each temperature probe. A thermistor is a temperature sensor. The thermistors are located at 10, 20, 30, 40, and 50 mm distance from the white enclosure. The thermistor located at 10 mm is known as the outer thermistor because, once installed into a plant, it is located towards the outside of the xylem whereas the inner thermistor is located towards the inside of the xylem.

The measurement zone of influence for each thermistor is approximately 5 mm radius.

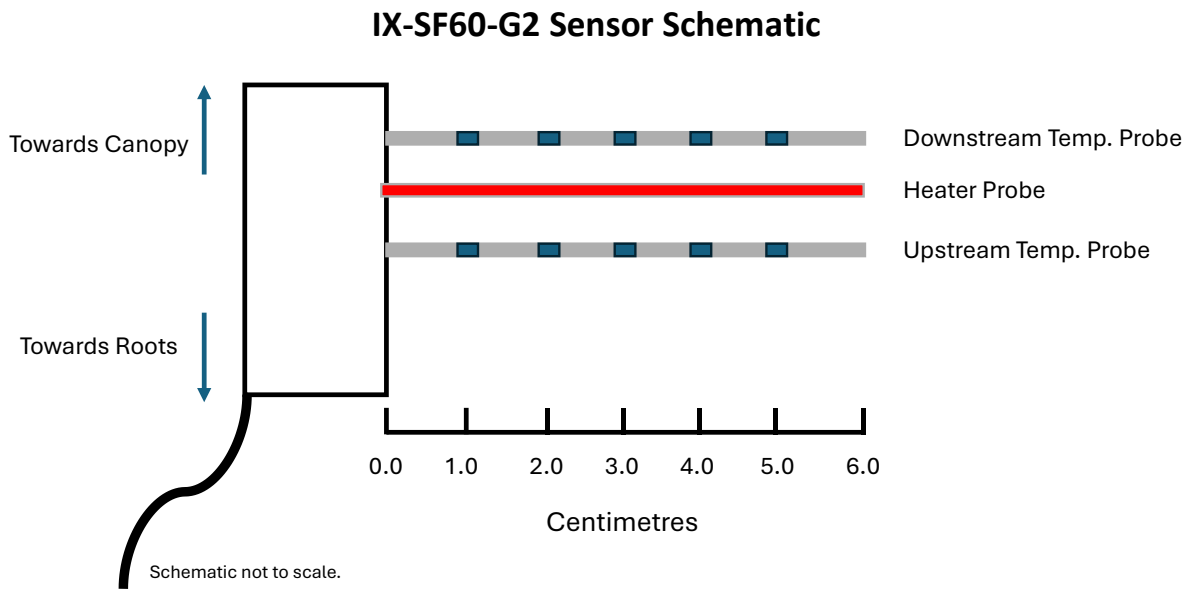

Figure 2. A schematic of the Implexx Sap Flow Sensor Gen 2 IX-SF60-G2 model.

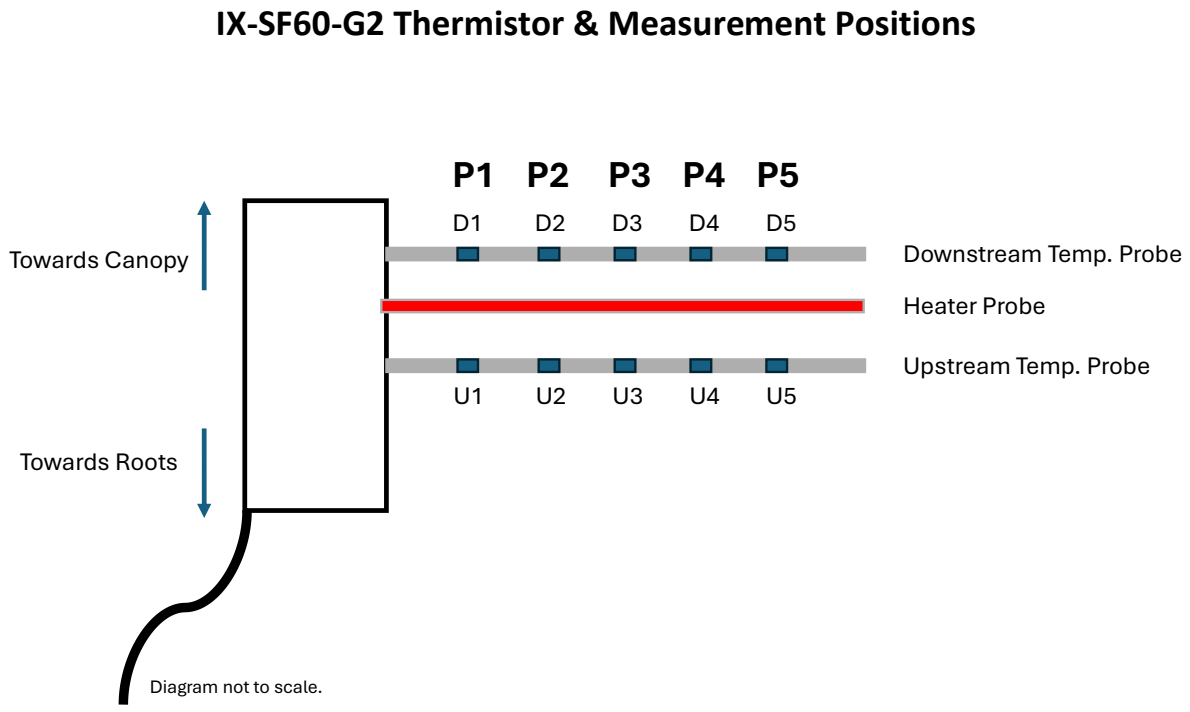

Figure 3. A schematic of the Implexx Sap Flow Sensor Gen 2 (IX-SF60-G2 model) indicating the downstream (D1, D2, D3, D4, D5) and upstream (U1, U2, U3, U4, U5) measurement points at positions 1, 2, 3, 4 and 5 (P1, P2, P3, P4, P5).

Theory – Sap Flow Measurements

The Implexx Sap Flow Sensor Gen 2 is based on the heat pulse family of measurements including dual method approach (DMA), heat ratio and Tmax. However, it is possible to extract raw temperature data from the sensor for alternative methods or for the user to build their own method. Implexx Sense strongly recommends the use of the dual method approach as this method measures the entire measurement range of sap flow in plants from reverse, to zero to extremely fast flow.

The dual method approach used in the Implexx Sap Flow Sensor Gen 2 was developed by Forster (2020). It is recommended that all users thoroughly read and understand Forster (2020):

Forster, M.A., 2020. The importance of conduction versus convection in heat pulse sap flow methods. Tree Physiol. 40 (5), 683–694.

https://doi.org/10.1093/treephys/tpaa009

The Conduction/Convection Heat Transfer Equation

The two-dimensional conduction/convection heat transfer equations for xylem was outlined by Marshall (1958):

$$\Delta T_d = \frac{q}{4\pi kt} \exp\left[-\frac{(x - V_h t)^2}{4kt}\right] \quad \text{Eq. 1}$$

$$\Delta T_u = \frac{q}{4\pi kt} \exp\left[-\frac{(x + V_h t)^2}{4kt}\right] \quad \text{Eq. 2}$$

where ΔT is the change in temperature following a heat pulse in the downstream (*d*- subscript, Eq. 1) and upstream (*u*- subscript, Eq. 2) temperature needles in an axial direction from the heater needle, q is heat input (W m^{-1}), k is thermal diffusivity (m^2 s^{-1}), V_h is heat velocity (m s^{-1}), t is time since heat pulse emission (s), and x is the distance (m) between the heater and temperature needles.

The V_h and k parameters are the convective and conductive components, respectively, and k is further defined as:

$$k = \frac{K}{\rho c}$$ Eq. 3

where K (W m^{-1} K^{-1}) is thermal conductivity and ρ (kg m^{-3}) and c (J kg^{-1} K^{-1}) are the density and heat capacity, respectively, of the sap and wood matrix. The parameters K, ρ and c require further resolution, based on wood and sap properties, stem water content, and more, with detailed procedures and calculations provided in the next section of the manual (see section titled "Correction Factors for Sap Flow Measurements").

Thermal Equilibrium and the Conduction/Convection Equation

Thermal equilibrium is defined as the equal change in the ratio of ΔT_d to ΔT_u for all V_h. Resolving equations 1 and 2, in combination with the equidistant, three-needle heat pulse probe design, shows that the ratio of ΔT_d to ΔT_u is equal for all V_h. This is thermal equilibrium: the relative change in downstream and upstream temperature needles, post-heat pulse, is in equilibrium for all values of V_h.

Thermal equilibrium is theoretically defined as (α is alpha and β is beta from the raw data outputs of the Implexx Sap Flow Sensor Gen 2):

$$\alpha = \beta$$ Eq. 4

where

$$\alpha = \ln\left(\frac{\Delta T_d}{\Delta T_u}\right)$$ Eq. 5

In practice, pre-heat pulse temperature is an average temperature over some duration prior to the release of the heat pulse (usually 10 seconds). The post-heat pulse temperature is defined as the average temperature between 60 and 80 seconds following the heat pulse.

The right-hand side of the thermal equilibrium equation is defined as:

$$\beta = \ln\left(\frac{\Delta T_{d,max}}{\Delta T_{u,max}}\right)$$ Eq. 6

where $\Delta T_{d,max}$ and $\Delta T_{u,max}$ are the difference between maximum temperature post-heat pulse and the pre-heat pulse temperature in the downstream and upstream temperature needles, respectively. Note that these parameters can also be an output from the Implexx Sap Flow Sensor Gen 2 (i.e., the M1! and M2! SDI-12 commands).

Thermal disequilibrium occurs when:

$$\alpha \neq \beta$$ Eq. 7

Thermal disequilibrium is significant because it means that the combined utilisation of equations 1 and 2 to resolve V_h is invalid. Either equation 1 or 2 can be used under conditions of thermal disequilibrium but not together. Under conditions of thermal disequilibrium, equation 1 would be used to resolve V_h because it is the heat transfer equation in the downstream direction (i.e. sap flowing from the roots to the canopy).

The Péclet Equation and the Péclet Number

The Péclet equation, also referred to as the Péclet number, is the ratio of conduction to convection. The Péclet equation is:

$$Pé = \frac{V_h x}{k}$$ Eq. 8

When the Péclet number equals one then conduction and convection are equal. Values less than or greater than a Péclet number of one indicates a conductive or convective dominated process, respectively. In the context of the Péclet equation, V_h is convection, k is conduction, and x is the characteristic length (i.e. the distance between the heater and temperature needles).

The Slow Rates of Flow (Heat Ratio) Equation

The Slow Rates of Flow Method, commonly referred to as the Heat Ratio Method (HRM), is a derived formula from combining equations 1 and 2 for characterising heat transfer in the downstream and upstream directions. The equation is:

$$V_h = \frac{\alpha k}{x}$$ Eq. 9

A modified version of equation 9 was introduced by Kluitenberg et al. (2007) to account for differences in heat pulse duration (t_0) and distance between downstream (x_d) and upstream (x_u) temperature needles from the heater needle:

$$V_h = \frac{2k\alpha}{x_d + x_u} + \frac{x_d - x_u}{t - (\frac{t_0}{2})}$$ Eq. 10

As the HRM is a combination of equations 1 and 2, it is only valid under conditions of thermal equilibrium.

The Relationship Between Thermal Equilibrium, Péclet and HRM Equations

The Péclet and HRM equations are algebraic re-arrangements of the other. Furthermore, via the inclusion of α and β into the equations, the relationship between thermal equilibrium, the Péclet and HRM equations can be theoretically demonstrated. That is, equations 4, 5, 6, 8 and 9 are equivalent:

$$Pé = \frac{V_h x}{k} = \alpha = \beta$$ Eq. 11

Therefore, the HRM equation describes thermal equilibrium.

The Tmax Equation

The Tmax method only requires a two-needle configuration where the temperature needle is positioned downstream to the heater needle. The Tmax formula was outlined by Cohen et al. (1981) as:

$$V_h = \frac{\sqrt{x_d^2 - 4kt_m}}{t_m} \quad \text{Eq. 12}$$

where t_m is the time to maximum temperature rise following the heat pulse.

The Tmax formula (eq. 9) is highly dependent on an accurate measurement of x_d and heat pulse duration (t_0). Therefore, to account for slight variations in these parameters, Kluitenberg and Ham (2004) and Kluitenberg et al. (2007) proposed the following equation:

$$V_h = \sqrt{\frac{4k}{t_0} ln\left(1 - \frac{t_0}{t_m}\right) + \frac{{x_d}^2}{t_m(t_m - t_0)}} \quad \text{Eq. 13}$$

As the Tmax is derived only from equation 1, and it requires just a downstream temperature needle, it can theoretically be used under conditions of thermal disequilibrium.

The Dual Method Approach (DMA)

The DMA is an algorithmic technique that utilises the optimal V_h derived from HRM at reverse/slow velocities and Tmax at faster velocities. Forster (2019, 2020) suggested using a critical threshold to switch between HRM and Tmax methods. A theoretical threshold/transition value is introduced based on equation 11. Values less than or equal to a Péclet number of one correspond to HRM whereas values greater than one correspond to Tmax. The algorithm for the theoretical DMA method, hereafter called $DMA_{Péclet}$, is:

If $\beta \leq 1$ *Then* V_h = HRM;

Else V_h = Tmax.

Wounding and Corrected Heat Velocity (V_c)

Following the correct determination of V_h, it is necessary to correct for sensor installation, as well as sap and wood properties, to calculate sap flux density. The next step after correctly calculating V_h is the calculation of heat velocity corrected for wounding, V_c. A wound correction factor is required due to the insertion of needles into xylem disrupting flow and the formation of tyloses. V_c (m s^{-1}) is calculated as:

$$V_c = aV_h + bV_h^2 + cV_h^3$$

Eq. 14

where *a*, *b*, and *c* are co-efficients that are calculated via finite-difference numerical modelling and vary with wound width, probe size, and spacing.

Sap Flux Density (J)

The next step is to convert V_c to sap flux density (J). A common conversion of V_c to J (m^3 m^{-2} s^{-1}; or more commonly expressed as: cm^3 cm^{-2} hr^{-1}) is via (Barrett et al. 1995):

$$J = \frac{V_c \rho_d (c_d + m_c c_w)}{\rho_w c_w}$$

Eq. 15

where ρ_d is sapwood dry density (kg kg^{-1}), c_d and c_w are the specific heat capacity of the dry wood matrix (1200 J kg^{-1} K^{-1}) and sap solution (4182 J kg^{-1} K^{-1}), respectively. ρ_w is the density of sap (assumed to be the density of water, 1000 kg m^{-3}) and m_c is sapwood moisture content (kg kg^{-1}; calculated as: $[w_f - w_d]/w_d$).

Note that equation 15 contains fixed and variable parameters. The fixed parameters are c_d, c_w, ρ_w and ρ_d whereas the variables are V_c and m_c. Variations in m_c occur seasonally, usually due to changing environmental conditions such as soil moisture availability, and, therefore, a periodic measurement of mc is required.

Total Sap Flow (Q)

Following the estimation of sap flux density (J), total sap flow can be calculated. Total sap flow (Q) is the sum of J for all measurement positions multiplied by sapwood area (A).

Total Sap Flow (Q) for the IX-SF60-G2 model is the sum of the sap flux density across the five measurement positions (P1, P2, P3, P4, P5 – see Figure 3 on page 11).

$$Q_{P1} = J_{P1}A_{P1} \quad \text{Eq. 16a}$$

$$Q_{P2} = J_{P2}A_{P2} \quad \text{Eq. 16b}$$

$$Q_{P3} = J_{P3}A_{P3} \quad \text{Eq. 16c}$$

$$Q_{P4} = J_{P4}A_{P4} \quad \text{Eq. 16d}$$

$$Q_{P5} = J_{P5}A_{P5} \quad \text{Eq. 16e}$$

$$Q_{total} = Q_{P1} + Q_{P2} + Q_{P3} + Q_{P4} + Q_{P5} \quad \text{Eq. 16f}$$

The Implexx-SF Sap Flow Excel Workbook

There is a limited ability to input, or change, correction factors via SDI-12 commands in the Implexx Sap Flow Sensor Gen 2. For a thorough investigation and research of correction factors, and to improve the overall accuracy of data, it is recommended to download the raw data (i.e., alpha, beta and Tmax data) and import these data to the Implexx-SF Sap Flow Excel Workbook. Detailed information, including manuals and guides, for the Excel Workbook can be found on the Implexx Sense website:

https://www.implexx.io/sap-flow/implexx-sf-sap-flow-excel-workbook/

Correction Factors for Sap Flow Measurements

Wound Diameter

Equipment Required:

- Callipers
- Dissecting blade
- Hand lens or dissecting microscope

Wounding is an inevitable consequence of drilling into the plant and inserting the sensor probes. For accurate sap flow data, it is critical that wounding is measured and corrected for in converting heat pulse velocity into sap flux density and sap flow.

The wound should be visually observable once the sensor probes have been carefully removed from the plant. You may need to scrape away, or remove, the bark with a dissecting blade to visually see the wound on the sapwood.

The wound is the hole where the sensor is inserted into the plant plus a ring, or donut, shape surrounding the hole. This is tyloses – or cell death to prevent infections from entering the plant.

Measure the wound diameter with a set of callipers. Measure the average of the three wounds from the three sensor probes.

Wound diameter value should range between 0.18 and 0.3 cm (centimetres).

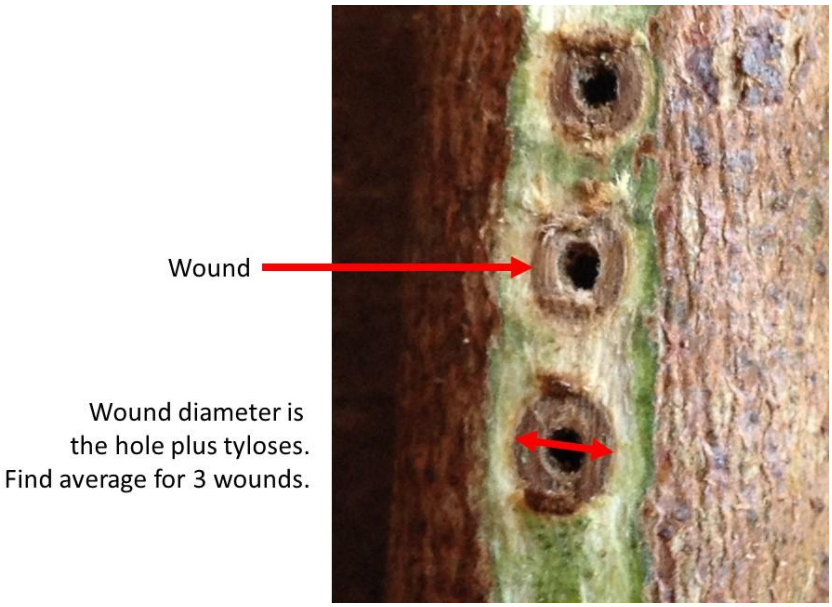

Figure 4. An example of a wound caused by probe/needle insertion into the xylem. The wound diameter is measured to the side of the drilled holes.

Sapwood Fresh Volume, Weight and Dry Weight

Frequency of Measurement:

Sapwood fresh volume, fresh weight, and dry weight are used to calculate both sapwood dry density and moisture content. A single measurement is sufficient for determining dry density. However, moisture content should be measured regularly, as it varies seasonally and with environmental conditions such as soil moisture availability. These variations should be quantified. Alternatively, sapwood or stem moisture content readings from the sensor can be used to monitor seasonal changes.

Equipment Required:

- Increment borer
- Secateurs
- Dissecting blade
- Callipers
- 3 or 4 decimal point weigh scale
- Drying oven

The sapwood fresh volume, weight and oven dry weight is measured to determine the wood bulk density and gravimetric moisture content of sapwood.

A sample of sapwood must be collected from your measured plant. For large trees, a sample can be collected using an increment borer. For small stems, a sample can be collected using secateurs and a dissecting blade.

It is important that only sapwood is sampled. Do not measure bark and/or heartwood.

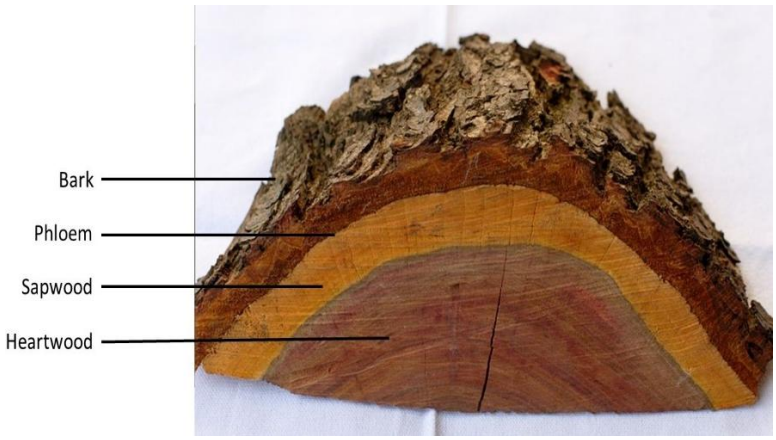

Figure 5. An example of the plant tissues within a tree with bark towards the outside of the tree, then phloem, and xylem (sapwood and heartwood).

Figure 6. An increment borer is shown taking samples of sapwood within a tree.

Sapwood Fresh Weight

Immediately following the collection of the sapwood sample, it is important that the weight of the sample is measured.

Ideally, the sample should be weighed immediately. However, in the field this may not be possible. Therefore, wrap the sample in parafilm or other material to prevent desiccation. Place the sample in a zip lock bag and into an Esky or ice container. You need to ensure that moisture loss is minimised.

Sapwood Fresh Volume

Immediately following measuring sapwood fresh weight, it is important that the shape, or volume, is measured.

With a sample from an increment borer, you can carefully cut the ends of the sapwood core to create a cylindrical shape. With a set of callipers, measure the height and diameter of the cylinder and calculate volume.

With a sample from a small stem or wood section, it may be possible to cut the sample into a cube, cuboid or cylinder to measure the volume.

Often, the shape will be irregular. For these samples, the volume can be determined following Archimedes' principle.

Sapwood Oven Dry Weight

Place the sample in a drying oven at a temperature of 70 °C to remove all moisture from the sample. Depending on the moisture content of the sample, it may take several hours or a couple of days to remove all moisture.

Every few hours, remove the sample from the drying oven and re-weigh. Once the weight is no longer decreasing, then all moisture has been dried from the sample. This is the oven dry weight.

Stem Diameter, Bark Depth and Sapwood Depth

Equipment Required:

- Diameter tape
- Callipers
- Increment borer

It is critical to measure the size of the plant to convert sap flux density into volumetric, or whole-plant, sap flow.

Measure the diameter of the plant where the sap flow sensor was installed with either a diameter tape for large trees or callipers for small stems.

Measure the bark depth, or radius, of your plant.

Measure the sapwood radius, or depth, at the location where the sap flow sensor was installed. Ideally, a cut stem is the most accurate approach to measure sapwood radius. For small stems a pair of secateurs can cut the stem. For large trees a chainsaw, operated by a qualified technician, may be required. Only operate a chainsaw under appropriate supervision and training.

Where it is not possible to cut a large tree, an increment borer can be used to measure sapwood radius. With the increment borer, sample to at least halfway into the tree. Remove the core and measure the sapwood length.

Note that sapwood depth may be irregular around the circumference of the tree. You may need to measure at several circumferential locations to better understand the distribution of sapwood.

Figure 7. Examples of the circumferential distribution of sapwood in two *Eucalyptus* spp. (tallowwood and ironbark) from New South Wales, Australia. The tallowwood on the right shows a relatively uniform distribution of sapwood. In contrast, the ironbark on the left is irregular.

Theory – Stem Water Content Measurements

What is stem water content?

Stem water content refers to the amount of water inside stems, trunks, branches, twigs, etc, of plants. Stem water content is also referred to as sapwood water content, moisture content, sapwood gravimetric water content, or sapwood volumetric water content.

Stem water content may be differentiated into bark, sapwood, heartwood water content, or a combination of bark, sapwood and heartwood water content. Therefore, it is more precise to differentiate stem water content into bark, sapwood or heartwood water content.

Figure 8 is an anatomical diagram of the stem showing the bark, phloem, xylem, sapwood and heartwood and the locations where water content may be estimated.

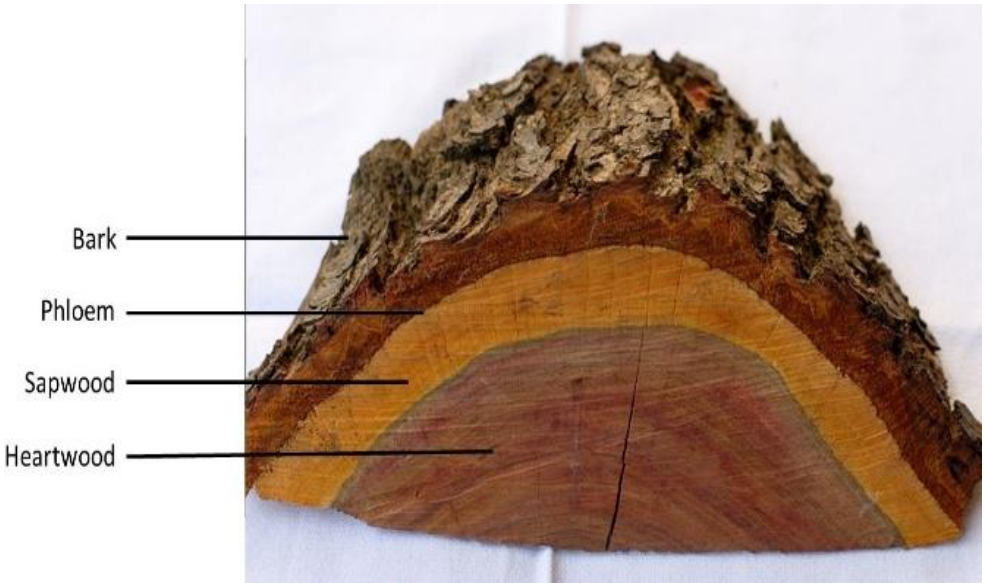

Figure 8. The anatomy of a representative dicotyledon woody stem. Typically, stem water content is measured in the sapwood and is therefore also referred to as sapwood water content. However, water content in the bark and heartwood can also be measured.

Why is stem water content important?

Stem water content is a measure of the hydration levels in stem tissues. Hydration, or the amount of water, is critical for a large range of plant physiological processes including transpiration, photosynthesis, reproduction, growth, organ development, cell structure and function, osmotic relations, and more.

Stem water content is also important for several parameters of interest to hydrologists such as storage (capacitance) and the abilities of plants to respond to soil moisture deficits, droughts and extreme weather events.

How is stem water content measured?

Stem water content is measured destructively or estimated with sensor technology.

Destructive measurements are the most accurate method to determine stem water content. But, as the name implies, it also means wounding, damaging, or harvesting the plant.

In trees, a sample is collected via a stem borer. The wet weight of the sample is quickly measured on a weigh scale. The sample is then oven dried to remove all moisture and the sample is reweighed to find the dry weight. The water content of the sample can then be calculated.

Sensor technology is an in-situ, continuous and non-destructive estimate of stem water content. Sensing technology is not a direct measurements of water content rather it is an estimate based on physical principles. This may include capacitance sensors measuring the dielectric permittivity of stems; or thermal sensors measuring the thermal properties of stems via thermal conduction. The dielectric permittivity or thermal properties of the stem are then converted to water content through a series of equations.

The Implexx Sap Flow Sensor estimates stem water content via thermal properties and thermal conduction.

Figure 9. The Implexx Sap Flow Sensor provides in-situ, non-destructive and continuous estimates of stem water content as well as sap flow and stem temperature.

How are water content and thermal conduction related?

Thermal conduction is the movement of heat in a sample via diffusion. The sample can be anything from plant material (i.e., stem or sapwood) to soil to rocks to water to fabric to metals and more.

Thermal conduction is dependent on several parameters including the amount of heat input into the sample, maximum change in temperature, and properties of the sample including its density, its specific heat capacity, the specific heat capacity of water (or sap within plants), and, most importantly for stem water content, the water content of the sample.

How is stem water content calculated from thermal properties?

The equation for volumetric stem water content (ϑ, %) is:

$$\theta = \frac{\rho c - \rho_d c_d}{\rho_w c_w} \qquad \text{Eq. 17}$$

where ρc (kJ m^{-3}) is volumetric heat capacity of the stem, ρ_d (kg m^{-3}) is dry wood density, c_d is heat capacity of dry wood (1.2 kJ kg^{-1} K^{-1}), ρ_w is the density of sap (1000 kg m^{-3}), and c_w is the heat capacity of sap (4.182 kJ kg^{-1} K^{-1}).

From equation 17, c_d, ρ_w and c_w are fixed parameters. Therefore, these parameters are assumed to be the same for all plants (although, strictly, these values vary slightly between species and with temperature and the careful, thorough researcher will check their own values).

The ρ_d parameter (denoted as DDW in the Implexx Sap Flow Sensor) is both a fixed and variable parameter. That is, ρ_d varies between species, varieties, individuals, and location within the plant (e.g., at the base of the trunk versus the branches). However, once wood has formed within plants ρ_d is then a fixed value at a specific location. That is, the density of wood does not change once it is formed. Therefore, ρ_d must be measured once at a location as close as possible to the sensor's installation site.

The parameter ρc is a variable in equation 17. Therefore, an accurate measurement of ρc is required to estimate stem water content. The parameter ρc is further defined as:

$$\rho c = \frac{(q/1000)}{e\pi x^2 \Delta T_m} \quad \text{Eq. 18}$$

where q is the heat pulse energy (J m^{-1}), x is the distance (m) between the heater and temperature probes, and ΔT_m (°C) is the maximum temperature following the heat pulse minus the pre heat pulse temperature.

The x parameter is usually assumed to be a fixed value although it can vary depending on the installation (see probe misalignment issues and application note). Additionally, x may vary over time as the plant grows, develops wounds, and undergoes other changes. Therefore, x should be carefully observed.

The q parameter is dependent on electronics and the application of a heat pulse. As q is electronically dependent it is assumed to be a fixed parameter, but it can vary with temperature and other properties. The Implexx Sap Flow Sensor measures q for every heat pulse and the value is included in the stem water content calculation.

The ΔT_m parameter is the variable directly correlated with stem water content. The correlation between ΔT_m and stem water content is negative where wet stems with high moisture content have relatively small ΔT_m values and dry stems with low moisture content have relatively large ΔT_m values.

How accurate is the Implexx Sap Flow Sensor in estimating stem water content?

The Implexx Sap Flow Sensor accurately estimates stem water content. Figure 10 shows the correlation between volumetric stem water content measured from an Implexx Sap Flow Sensor and actual volumetric stem water content measuring with a drying oven. The samples were measured from 4 different species. Analysis found that the accuracy is approximately 3%.

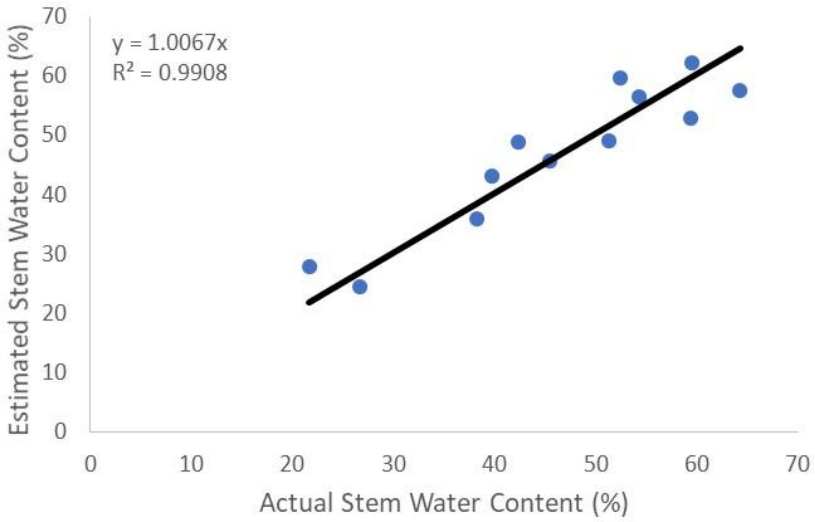

Figure 10. A comparison of actual stem water content, measured via destructive sampling technique, and estimated stem water content via the Implexx Sap Flow Sensor.

Radial measurements of stem water content

The Implexx Sap Flow Sensor can estimate stem water content at multiple depths into the stem. Known as “radial profiling”, measurements are undertaken towards the outside (“outer”) and inside (“inner”) portions of the stem (Figure 11). The 30 mm length needles of the Implexx Sap Flow Sensor have a temperature sensor (thermistor) at 10 mm (outer) and 20 mm (inner) depth. Therefore, these two measurement locations can be used to resolve stem water content at different locations within the stem’s anatomy.

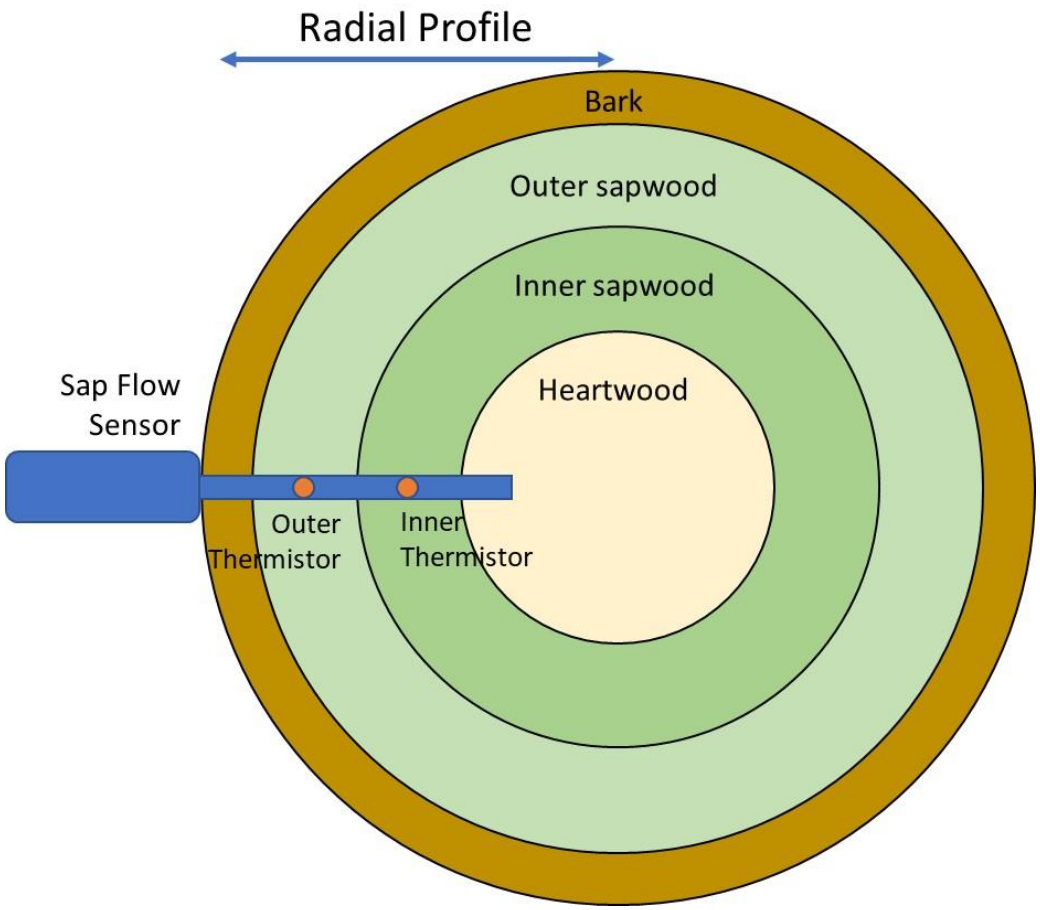

Figure 11. The radial profile of a stem is that portion from the outside of the bark to the middle of the heartwood. The radial profile may also be extended across the diameter of the stem. The Implexx Sap Flow Sensor measures at 2 locations along the radial profile: outer (towards the outside of the stem) and inner (towards the inside of the stem).

Understanding the dynamics of water content across the radial profile will provide invaluable insights to plant adaptation and physiology. For example, in some plants the inner portion of the stem, or even the bark, may be a zone of water storage (capacitance) that is important during time of soil moisture deficit. The importance of such storage, and its dynamics, can only be known if it is measured.

The high spatial resolution of the Implexx Sap Flow Sensor is a distinct advantage over other sensing technology that measure stem water content. For example, soil water content sensors that are installed inside trees, such as capacitance probes, or time domain reflectometry (TDR) probes, integrate water

content measurements over the entire length of the probe. This length may be 50 mm or longer and can cross different stem tissue such as bark, sapwood and heartwood. These probes have a poor spatial resolution and misinterpretation of data may occur (Figure 12).

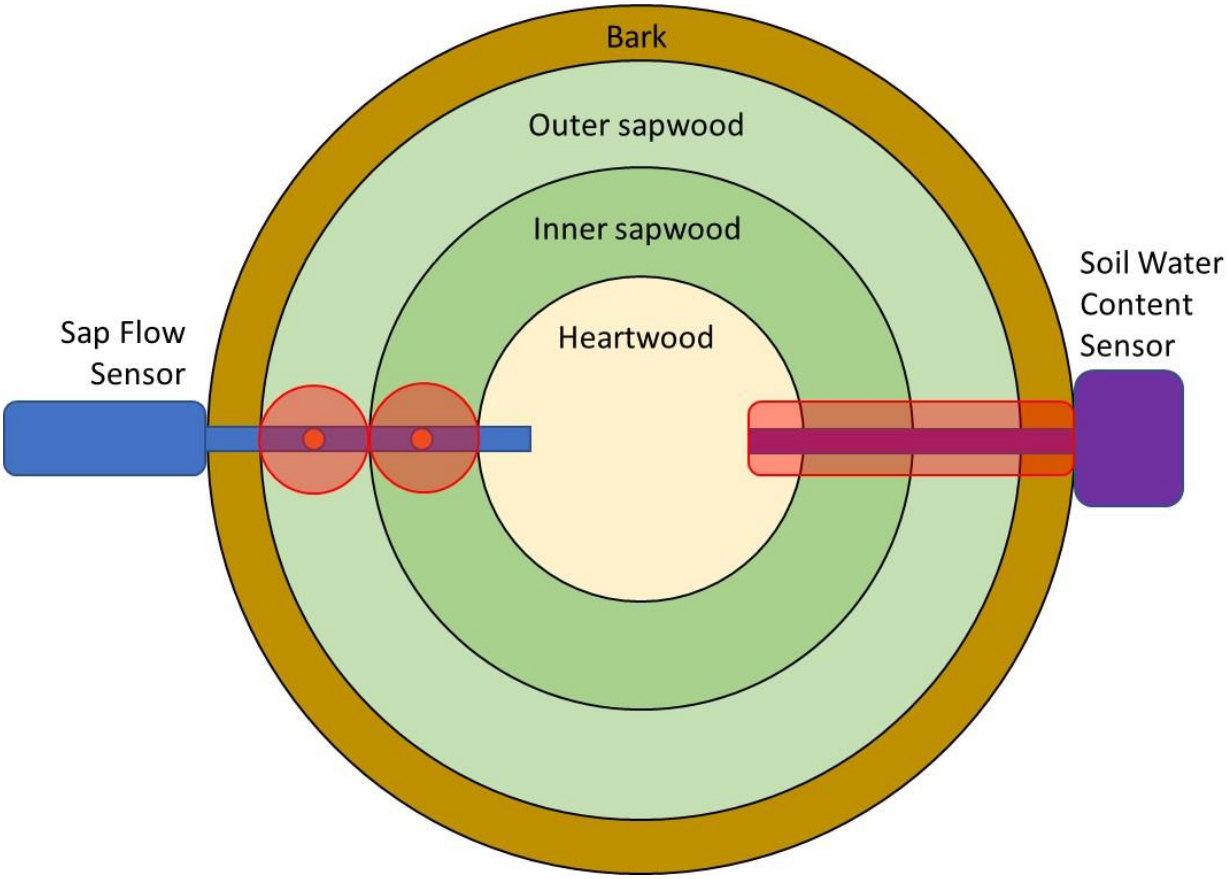

Figure 12. The spatial resolution of the Implexx Sap Flow Sensor, based on thermal properties, versus a soil water content sensor based on either capacitance or TDR. The zone of influence, or spatial resolution, is highlighted in red.

Stem water content under high sap flow conditions

The estimation of stem water content via the theory of thermal conduction assumes that there is zero thermal convection. That is, the sap, or fluid, inside the stem, during a measurement cycle, is assumed to be static or non-moving. This assumption is found in equation 17 where there is no parameter for velocity or convection.

Therefore, stem water content estimated via thermal properties is most accurate under zero, or very slow, sap flow conditions. Such conditions occur during the night, typically in the pre-dawn period approximately 1 to 2 hours prior to sunrise. It is recommended that stem water content is measured currently.

Under high sap flow conditions, the estimation of stem water content via a thermal sensor will be drier than actual stem water content. This result is found from equation 18 where ΔT_m is influenced by sap flow. Under high flow conditions, ΔT_m is relatively larger due to heat convection. An increase in ΔT_m causes ρc to decrease (because ΔT_m is the denominator, or a parameter below the line, in equation 18). A decrease in ρc in equation 17 will lead to a smaller stem water content value.

One possible approach to estimate stem water content under high sap flow conditions is to install the probes perpendicular to the direction of sap flow (i.e., the yellow circles in Figure 13). Although, caution with this approach should be taken as this method has not been extensively researched or tested. Also, it is not possible to estimate sap flow with this style of installation.

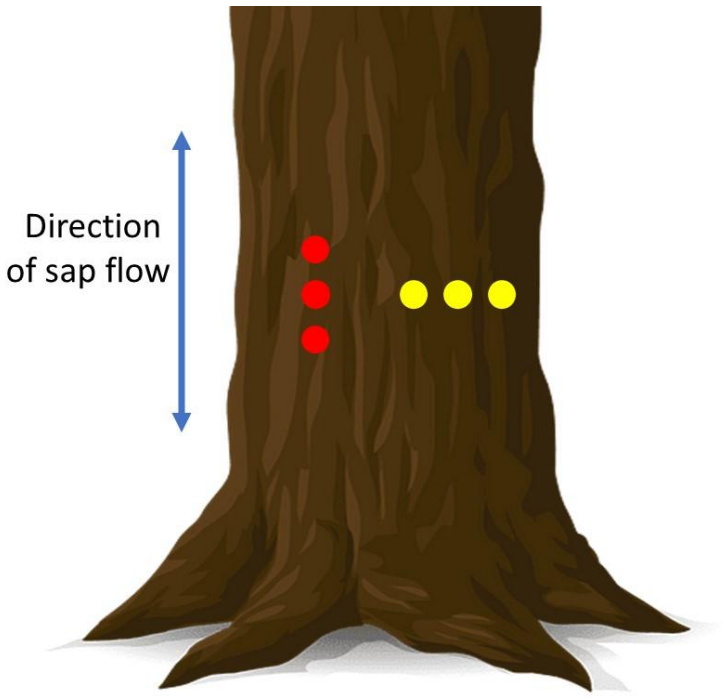

Figure 13. Under high sap flow, stem water content may be estimated by installing the sensor perpendicular to the assumed direction of sap flow. The red circles represent a typical sap flow sensor

installation where the sensor is installed parallel to the direction of flow. The yellow circles represent a sensor installation perpendicular to the direction of sap flow. Caution should be exercised with this approach as it has not been extensively tested or investigated.

Negative stem water content?

The observable range of values for stem water content is between 0 % (completely dry) and 100 % (pure water). Typically, values range between 10 % and 80 % as some moisture is always retained in the stem and the stem cannot be pure water.

However, the Implexx Sap Flow Sensor may output a negative stem water content or a value greater than 100 %.

The sensor is not faulty. Rather, the parameters from equations 17 and 18 have not been configured correctly. A correct configuration will remove negative or erroneous values.

The two most important parameters from equations 17 and 18 that must be configured correctly are dry sapwood density (ρ_d), also known as dry density of sapwood (DDW), and the distance (x) between the heater and temperature probes. The importance of ρ_d to stem water content is shown in equation 17. Similarly, x is important in equation 18. The parameters ρ_d and x are explained in detail in the section above, “How is stem water content calculated from thermal properties?”.

Further information, and how to measure ρ_d and x, are provided in the application notes “How to measure sapwood density” and “Correction for probe misalignment” on the Implexx Sense website.

Installation – Overview

Proper installation of the Implexx Sap Flow Sensor is critical for accurate measurements. Although the IX-SF30-G2 and IX-SF60-G2 sensor models require different installation techniques, there are many similarities including:

- Safety first! Ensure proper safety glasses and personal protective equipment are worn.
- Watch the YouTube installation videos! Watch all the videos and then watch them again! A link to the videos is below.
- Do not rush or be aggressive with the drilling. This will only damage the plant and break drill bits or lead to personal injury.
- Do not cable tie the sensor directly against the tree – see Figures 17 and 18.

Installation – Videos

Users are encouraged to watch all available installation videos. The videos contain different information, as well as tips and best practices, and are all extremely beneficial.

- IX-SF60-G2 installation: https://www.youtube.com/watch?v=TxYqI1C2wWc
- IX-SF30-G2 installation: https://www.youtube.com/watch?v=QJXdQWPkfeE
- Removing sensors from tree: https://www.youtube.com/watch?v=FxIJ3iFw7XI

Installation – A Quick Guide

Step 1: Measure trunk diameter and bark depth.

Measure the trunk diameter (TDD) and bark depth (BDD). Enter these values into the Implexx Sap Flow Sensor via the SDI-12 commands (see page 51).

Step 2: Measure sapwood density (DDW).

Measure the dry sapwood density (DDW) with a stem borer, calliper, drying oven, and weigh scale. Enter the DDW value into the Implexx Sap Flow Sensor via the SDI-12 commands (see page 51).

Step 3: Apply grease.

Apply a generous amount of grease to the stainless-steel sleeves and needles of the sap flow sensor.

Set aside the sleeves and sensor for later installation.

Step 4: Mount drill guide.

Tightly secure the drill guide to the tree using the straps. It is important the base plate never moves during the drilling process. Therefore, ensure the guide is firmly locked in place.

Step 5: Start drilling.

Start with the top brick and drill all three holes.

Drill with short, sharp repetitions.

It is important to minimise damage to the wood. Do not burn the wood (or create smoke) with long, aggressive drilling.

Step 6: Swing brick and continue drilling.

Carefully, swing aside the top brick. Care must be taken to not move the base plate of the drill guide. So, when swinging aside the bricks, support the drill guide with your free hand.

Continue drilling holes, and swinging aside each brick layer, until all layers, including the base plate, have been drilled.

Important: Clean the drill bit.

During the drilling process, frequently clean the drill bit.

Clean the drill bit at least once per hole or repetition.

It is important the drill bit remains clean and sharp.

Step 7: Insert sleeves.

After drilling the final hole, quickly remove the drill guide from the trees and insert the stainless-steel sleeves into the holes.

Use the sleeve insertor to push the sleeves into the tree.

NEVER use the sensor to insert the sleeves.

Step 8: Install the sensor.

Install the sensor's needles into the stainless-steel sleeves.

Step 9: Insulate the sensor.

Insulate the sensor with heavy duty reflective material such as builder's wrap.

Support the reflective material with a tie above and below the sensor.

NEVER tie the sensor directly against the tree.

Important: NEVER do this!

NEVER cable tie, or strap, the sensor directly against the tree.

The tree grows outwards, the tie pushes inwards, and the result is a crushed and damaged sensor.

Installation – Thick Bark

Step 1: Prepare drill guide.

Ensure the wings modules have been installed and tightly secured with the bolts onto the base plate of the IX-SF60-G2 drill guide.

Step 2: Mark the tree.

Select a location on the trunk for sensor installation. Mark a rectangle shape on the tree slightly larger than the area of the drill guide. The bark will be removed from this area.

Step 3: Remove bark.

With a chisel and hammer, carefully and methodically remove the bark.

Approximately 5 mm of bark thickness should remain on the tree. This thick layer of bark will protect the sapwood from desiccation.

Step 4: Mount the drill guide.

The drill guide's base plate must never move during the drilling process. Therefore, ensure the drill guide is very tightly locked against the tree.

Once the drill guide is secured, following the installation steps for the IX-SF60-G2 outlined on pages 36 to 37.

Installation – Additional Details

In this section, additional details on the installation of the IX-SF60-G2 Implexx Sap Flow Sensor is given. This information should be used in combination with the Quick Overview section of this manual. This section elaborates on the installation process, giving finer details on the various steps.

Step 1: Select an installation site

- (a) Choose a representative or study tree of interest.

- (b) If you are installing a single sensor on the tree, install the sensor on the north face (if you are in the southern hemisphere) or south face (if you are in the northern hemisphere).

- (c) If you are installing two sensors, install one on the north and south face; if you are installing four sensors, install one on the north, south, east and west face, and so on.

- (d) To measure whole tree water use, install the sensor beneath lowest branch. That is, install the sensor beneath all the leaves so you are measuring the entire canopy. Avoid any obvious scars, decay, wounding, damage, etc.

- (e) It is not always critical but try and install the sensor above the root stock.

- (f) The golden rule is consistency. For all your installation sites on different trees, install the sensor in a similar height, aspect and trunk characteristics.

Step 2: Measure tree and wood parameters

- (a) Measure trunk diameter (TDD), in centimetres, where the sensor will be installed.

- (b) Measure bark depth (BDD), in centimetres, close by to where the sensor will be installed.

Step 3: Measure dry density of wood (DDW) also known as sapwood density

- (a) DDW is a critical parameter for the calibration co-efficient. You can either measure it directly on your tree with a stem borer or contact Implexx Sense for more information.

- (b) DDW should be measured as grams per centimetre cubed (g/cm^3). Values range between 0.100 and 1.200 g/cm^3 with typical values ranging between 0.400 and 0.800 g/cm^3.

IMPORTANT TIP!

The second set of steps is to configure your sap flow sensor for your installation site. You will need to know trunk diameter (TDD), bark depth (BDD) and dry density of wood (DDW). You will also need to have some knowledge or experience with configuring SDI-12 communication style sensors. Implexx Sense can provide a device where you can talk directly to the sap flow sensor via SDI-12 communication.

Step 4: Configure SDI-12 settings in the sap flow sensor

- (a) Consult the sap flow sensor integrator's guide for complete details on the SDI-12 settings available in the sap flow sensor.

- (b) Use the following SDI-12 commands to perform these basic configuration functions:

- (c) ?! ENTER – returns the sensor's SDI-12 address. The default address is 0.

- (d) 0XTDD! ENTER – returns trunk diameter value for sensor address 0. Default value is 10.0 cm.

- (e) 0XTDD=24.3! ENTER – changes the trunk diameter to 24.3 cm. Instead of 24.3, insert the value for your trunk diameter which you measured in Step 2(a).

- (f) 0XBDD! ENTER – returns bark depth value for sensor address 0. Default value is 0.5 cm.

- (g) 0XBDD=0.2! ENTER - changes the bark depth to 0.2 cm. Instead of 0.2, insert the value for your bark depth which you measured in Step 2(b).

- (h) 0XDDW! ENTER – returns dry density of wood for sensor address 0. Default value is 0.400 g/cm^3.

- (i) 0XDDW=0.558! ENTER – changes the dry density of wood to 0.558 g/cm^3. Instead of 0.558, insert the value for your dry density of wood measured in Step 3.

- (j) You may have more than one SDI-12 sensor connected to your bus or data acquisition unit. SDI-12 sensors can never have the same address. Therefore, you will need to change the address of at least one SDI-12 sensor. To change an address, use the following command: 0A1! ENTER. This command will change sensor address 0 to address 1.

- (k) your sap flow sensor is now configured and ready to install into the tree.

Step 5: To remove or not remove bark?

See diagrams on page 6 and 7 for detailed information.

- (a) Ideally, you should minimise the impact or damage on the tree when installing a sap flow sensor. Therefore, it is best not to remove bark unless necessary.

- (b) Bark should only ever be removed if it is thicker than 0.5 cm depth. In Step 2(b), if you measured bark depth (BDD) as greater than 0.5 cm, then you will need to remove some bark. If the BDD value is less than 0.5 cm, then do not remove bark.

- (c) If bark depth (BDD) is greater than 0.5 cm, carefully remove bark, with a dissecting blade or chisel, so that BDD equals 0.5 cm.

Step 6: Apply thermal grease to the needles or probes

- (a) Before you start drilling, it's always a good idea to apply thermal grease to the sap flow sensor needles. Application of grease to the stainless-steel sleeves is also recommended.

Step 7: Drilling into the tree

- (a) Strap or cable tie the drill guide to the tree. Ensure the 3-holes on the drill guide are aligned with the direction of sap flow. Ensure the drill guide does not move during the installation process.

- (b) Insert the drill bit into the chuck of the drill. You only need to insert the drill bit 2 or 3 mm into the chuck.

- (c) Start drilling into the tree.

- (d) Minimise your impact on the tree by drilling in short, sharp steps. You should only drill a few millimetres at a time and frequently cleaning the flute of the drill bit.

- (e) Golden rule – short, sharp and clean cuts!

- (f) Only remove the drill guide after you have completed drilling all 3 holes. If the drill guide is removed before this, you will need to start again.

Step 8: Inserting the sap flow sensor into the tree

- (a) Remove the drill guide (only after all 3 holes have been completely drilled through).

- (b) As quickly as possible, insert the 3 stainless steel sleeves into the drilled holes.

- (c) The sleeves should slide into the holes firmly but with no resistance. The sleeve insertor device can be used to push the sleeves into the tree (never use the sensor to push the sleeves into the tree!).

- (d) After the sleeves have been completely inserted into the tree, the sap flow sensor needles slide effortlessly into the sleeves.

- (e) Always position the outer thermistor at 0.5 cm depth beneath the bark or into the sapwood. See diagrams on pages 6 and 7 for further information.

WARNING!

The sap flow sensor must always be installed so the outer thermistor is at 0.5 cm depth into the sapwood. If the bark depth (BDD) is less than 0.5 cm, this will mean a small portion of the sap flow needles will not be inside the tree. This is not a problem. Simply insulate the exposed portion of the needles with foam and aluminium foil.

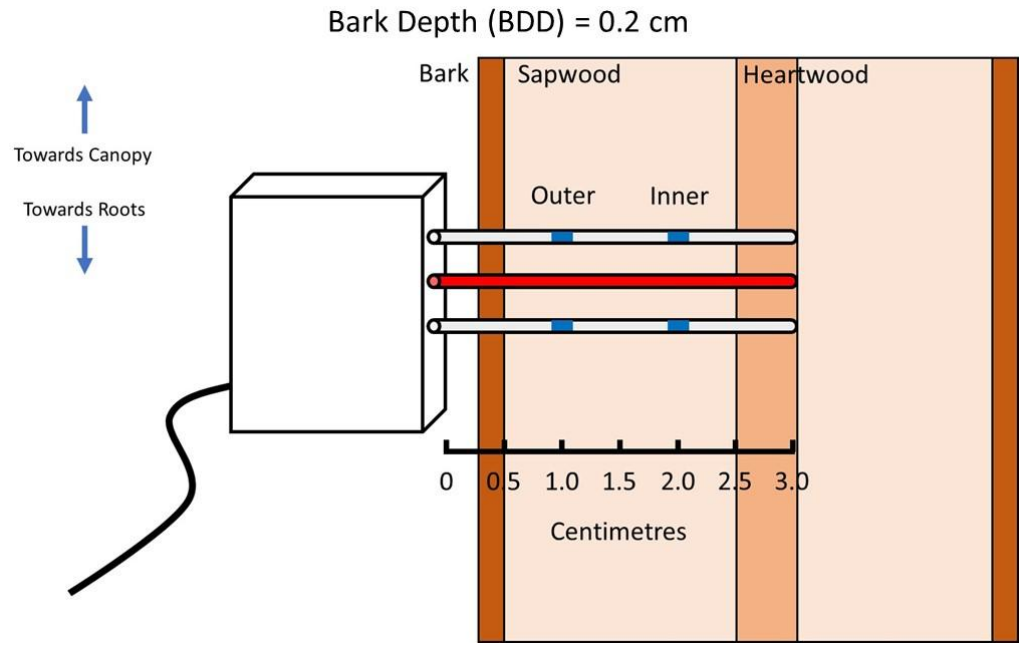

Figure 14. Thinner bark: a portion of the probes will be outside of the tree. Insulate this with foam/aluminium.

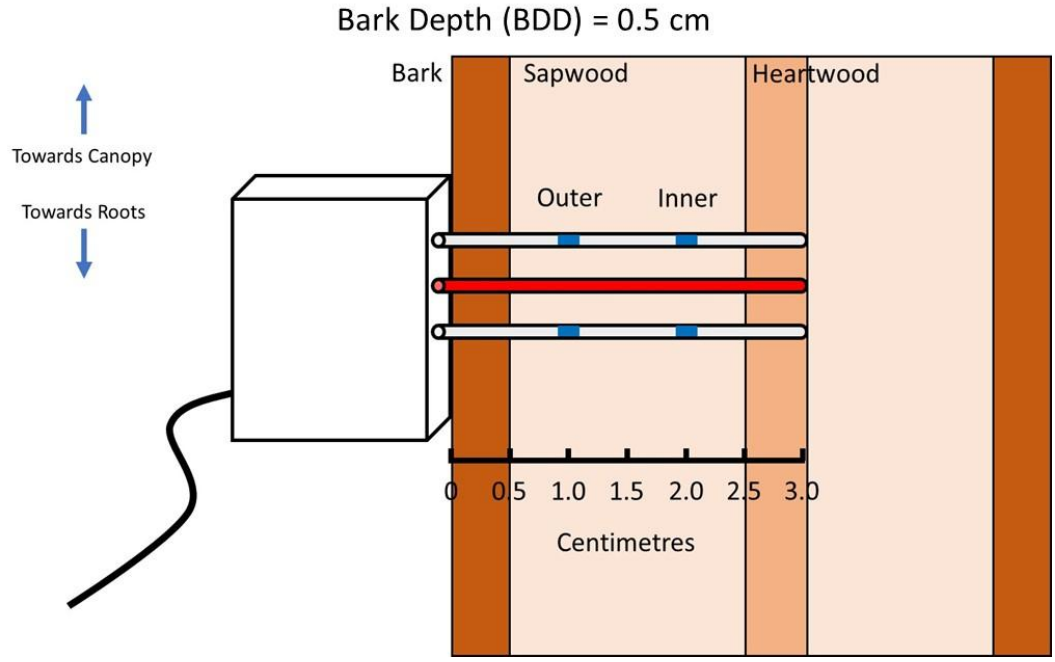

Figure 15. Do not remove any bark when thickness is approximately 0.5cm.

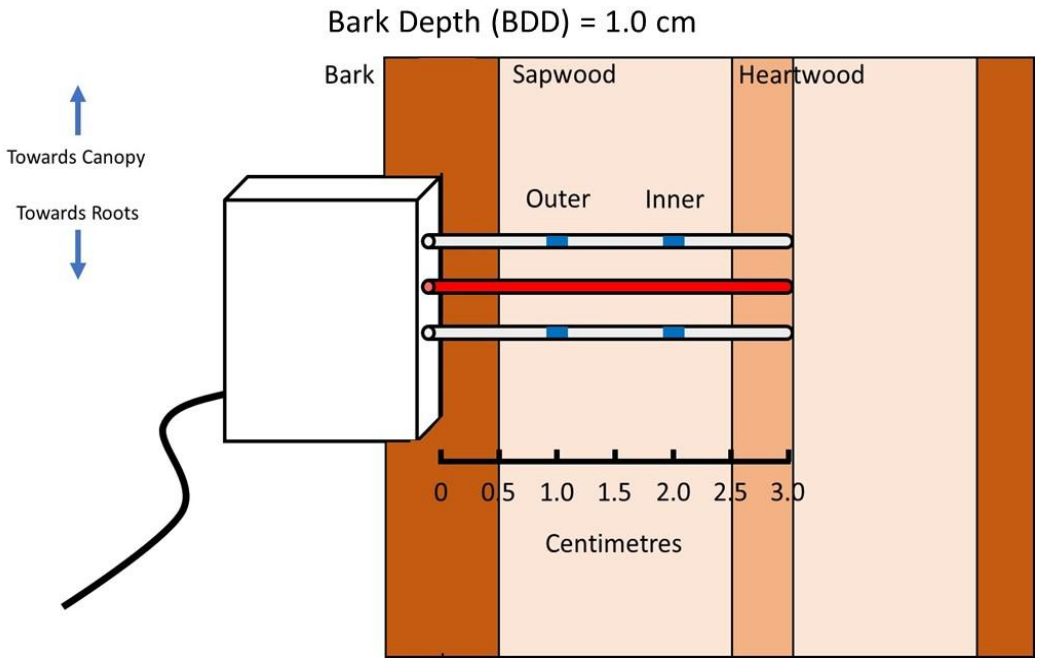

Figure 16. Thicker bark: carefully remove a portion of the bark with a dissecting blade or chisel until bark depth is approximately 0.5 cm.

Step 9: Insulate Sensor Installation with Reflective Insulation Material (builder's wrap)

- (a) Wrap a generous amount of reflective insulation material (also known as "builder's wrap") around the sensor and stem. This insulates the sensor from direct sunlight and external heat to avoid any errors associated with thermal gradients.

- (b) BUT do not cable tie the sensor directly against the stem. The stem grows outwards, and the cable tie pushes inwards. Therefore, fixing the sensor directly against the stem with a cable tie will crush and destroy the sensor. Fix the cable tie above and below the sensor.

Figure 17. A sensor with reflective insulation material (also known as “builder’s wrap”). BUT DO NOT CABLE TIE THE SENSOR DIRECTLY AGAINST THE TREE!

Figure 18. **NEVER DO THIS!** Do not tie the sensor directly against the tree because this will damage the sensor and void warranty.

Step 10: Connect the sap flow sensor cable to the data unit

- (a) The sap flow sensor has a 3-core (wire) cable that must be connected to a data acquisition unit, data logger or data transmission unit. Wiring: Red – 12 VDC power; Black – ground; White – data. Or: Brown – 12VDC power; Green – ground; White – data.

Step 11: Tidy up the installation site

- (a) Ensure there is no tension on the cables or wire. Always place cable inside conduit.

Step 12: Start collecting data

- (a) Ensure your data unit is properly programmed, connected to enough power (e.g. solar panels and batteries).

WARNING!

The most frequent data collect interval is 10 minutes. An SDI-12 M! command should never be sent to the sap flow sensor more frequently than 10-minute intervals.

Wiring

Wiring Sensor to a data logger, Implexx Sensor Hub (IX-HUB), or other device:

Green -> Ground

White -> Data

Brown -> Power (12 VDC)

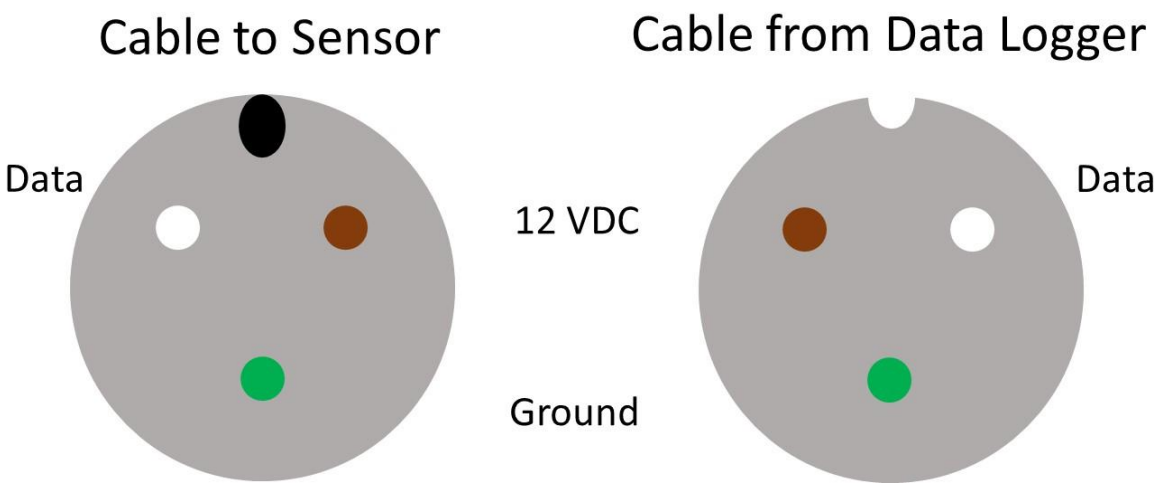

Figure 19. The wiring diagram for the cable connector. Ensure the cable connector is oriented correctly as indicated by the groove.

SDI-12 Commands – The Basics

Implexx Sense assumes the user has some familiarity with the SDI-12 protocol and commands. For an introduction to SDI-12, visit the SDI-12 Support Group website:

https://sdi-12.org/

To execute the SDI-12 commands, the Implexx Sap Flow Sensor must be connected to an SDI-12 enabled device. Implexx can provide an SDI-12 device, if required. Alternatively, the following brands and models are often used:

- Campbell Scientific: any logger model with Terminal Emulator, including CR350 or CR1000X.
- TekBox: TBS03 device.
- YDOC data logger.

An SDI-12 sensor usually has a default address, or unique identifier, as the number “0” (zero). If multiple SDI-12 sensors are connected to a single data logger, then each sensor must have a unique address. The sensor address may be a number between “0” and “9”, lower case letters between “a” and “z”, or upper case letters between “A” and “Z”.

To discover the SDI-12 address of a sensor, execute the following command:

?!

The number or letter which then appears is the sensor’s address. The user can change the sensor’s address, if required (see next section SDI-12 Commands – Sensor Set Up).

The format of an SDI-12 command is address-command-!

To execute the SDI-12 command, the user must press ENTER after the exclamation mark (!).

For example, the following is the SDI-12 command to change a sensor’s address from “0” to “a”:

0Aa!

Where 0 is the default address of the sensor, A is the SDI-12 command for change of address, a is the new sensor address, and ! is the exclamation mark. The user must press ENTER after !

To read a measurement value from the sensor, the following SDI-12 command is executed:

0C!

Following the execution of this SDI-12 command, a line with letters and numbers will appear. For example, for the IX-SF30-G2 Implexx Sap Flow Sensor, the following will appear:

0C! 012409

Where 0 is the sensor’s address, “124” is the time, in seconds, until a measurement from the sensor is available, and “09” is the number of parameters that will be returned.

In this example, after 124 seconds the user will need to execute the following command to retrieve the readings from the sensor:

0D0!

0D1!

Where D means “retrieve data”.

Following the execution of the D! command, another string of numbers and symbols will appear. For example, for the IX-SF30-G2 Implexx Sap Flow Sensor the following will appear:

0+0.120+2.44+3.10+0.20325+0.25789

0+0.17861+0.22075+98.584+94.373

For the IX-SF30 model, these numbers mean (or see Table in next section for a detailed explanation):

“0” – sensor address

“+0.120” – Total Sap Flow (the “+” symbol represents a positive number. There may also be a “-“ symbol which will indicate a negative number).

“+2.44” – Sap Flux Density (outer position)

“+3.10” – Sap Flux Density (inner position)

“+0.20325” – alpha (outer position)

“+0.25789” – alpha (inner position)

“0” – sensor address

“0.17861” – beta (outer position)

“0.22075” – beta (inner position)

“98.584” – tmaxT (outer position)

“94.373” – tmaxT (inner position)

For detailed information on additional SDI-12 commands, visit the SDI-12 community webpage:

https://sdi-12.org/

SDI-12 Commands – Sensor Set Up

The following commands are often required during the installation and set up of the Implexx Sap Flow Sensor. A comprehensive guide to all available SDI-12 commands in the IX-SF30-G2 and IX-SF60-G2 models are found in the tables in the following sections.

- **Sensor Address**
  - The default sensor address is “0” (zero).
  - SDI-12 command to change sensor address from “0” to “a”:
    - 0Aa!
  - SDI-12 command to change sensor address from “a” to “K”:
    - aAK!

- **Trunk Diameter (TDD)**
  - The default trunk diameter (TDD) is 10 cm.
  - SDI-12 command to change TDD to 24.3 cm:
    - 0XTDD=24.3!
  - SDI-12 command to change TDD to 6.8 cm:
    - 0XTDD=6.8!

- **Bark Depth (BDD)**
  - The default trunk diameter (BDD) is 0.5 cm.
  - SDI-12 command to change BDD to 0.3 cm:
    - 0XBDD=0.3!
  - SDI-12 command to change BDD to 1.8 cm:
    - 0XBDD=1.8!

- **Sapwood Dry Density (DDW)**
  - The default sapwood dry density (DDW) is 0.700 g/cm^3.
  - SDI-12 command to change DDW to 0.581 g/cm^3:
    - 0XDDW=0.581!
  - SDI-12 command to change TDD to DDW to 0.922 g/cm^3:
    - 0XTDD=0.922!

SDI-12 Commands – IX-SF60-G2

The following table summarises the available SDI-12 commands in the IX-SF60-G2 Implexx Sap Flow Sensor Gen 2 model. For further details on integrating the sap flow sensor with your SDI-12 enabled device, download the Implexx Sap Flow Sensor Gen 2 Integrator's Guide from the Implexx Sense website:

https://www.implexx.io/manuals-and-guides/

SDI-12 Command	Parameter	Units	Description
C!	SapFlowTotal	L/hr	Total sap flow (Eq. 16f).
Sap Flow and Sap Flux Density Outputs	SFD_Position1	$cm^3/cm^2/hr$	Sap flux density at the first measurement position (Eq. 15).
	SFD_Position2	$cm^3/cm^2/hr$	Sap flux density at the second measurement position (Eq. 15).
	SFD_Position3	$cm^3/cm^2/hr$	Sap flux density at the third measurement position (Eq. 15).
	SFD_Position4	$cm^3/cm^2/hr$	Sap flux density at the fourth measurement position (Eq. 15).
	SFD_Position5	$cm^3/cm^2/hr$	Sap flux density at the fifth measurement position (Eq. 15).
C1!	Alpha_Position1	dimensionless	The ratio of temperature in the downstream over the upstream after the heat pulse at the first measurement point (Eq. 5).
Temperature ratio data used for heat ratio, or slow rates of flow, calculations.	Alpha_Position2	dimensionless	The ratio of temperature in the downstream over the upstream after the heat pulse at the second measurement point (Eq. 5).
	Alpha_Position3	dimensionless	The ratio of temperature in the downstream over the upstream after the heat pulse at the third measurement point (Eq. 5).
	Alpha_Position4	dimensionless	The ratio of temperature in the downstream over the upstream after the heat pulse at the fourth measurement point (Eq. 5).
	Alpha_Position5	dimensionless	The ratio of temperature in the downstream over the upstream after the heat pulse at the fifth measurement point (Eq. 5).
	Beta_Position1	dimensionless	The ratio of maximum temperature rise after the heat pulse in the downstream over the upstream at the first position (Eq. 6).

	Beta_Position2	dimensionless	The ratio of maximum temperature rise after the heat pulse in the downstream over the upstream at the second position (Eq. 6).
	Beta_Position3	dimensionless	The ratio of maximum temperature rise after the heat pulse in the downstream over the upstream at the third position (Eq. 6).
	Beta_Position4	dimensionless	The ratio of maximum temperature rise after the heat pulse in the downstream over the upstream at the fourth position (Eq. 6).
	Beta_Position5	dimensionless	The ratio of maximum temperature rise after the heat pulse in the downstream over the upstream at the fifth position (Eq. 6).
C2!	tmaxT_PositionD1	seconds	The time to maximum temperature rise after the heat pulse at the first, downstream position.
Time to maximum temperature rise used in the Tmax calculation.	tmaxT_PositionD2	seconds	The time to maximum temperature rise after the heat pulse at the second, downstream position.
	tmaxT_PositionD3	seconds	The time to maximum temperature rise after the heat pulse at the third, downstream position.
	tmaxT_PositionD4	seconds	The time to maximum temperature rise after the heat pulse at the fourth, downstream position.
	tmaxT_PositionD5	seconds	The time to maximum temperature rise after the heat pulse at the fifth, downstream position.
	tmaxT_PositionU1	seconds	The time to maximum temperature rise after the heat pulse at the first, upstream position.
	tmaxT_PositionU2	seconds	The time to maximum temperature rise after the heat pulse at the second, upstream position.
	tmaxT_PositionU3	seconds	The time to maximum temperature rise after the heat pulse at the third, upstream position.
	tmaxT_PositionU4	seconds	The time to maximum temperature rise after the heat pulse at the fourth, upstream position.
	tmaxT_PositionU5	seconds	The time to maximum temperature rise after the heat pulse at the fifth, upstream position.

C3!	SWC_PositionD1	%	Stem (sapwood) water content in the first, downstream position (Eq. 17).
Stem Water Content (equation 17)	SWC_PositionD2	%	Stem (sapwood) water content in the second, downstream position (Eq. 17).
	SWC_PositionD3	%	Stem (sapwood) water content in the third, downstream position (Eq. 17).
	SWC_PositionD4	%	Stem (sapwood) water content in the fourth, downstream position (Eq. 17).
	SWC_PositionD5	%	Stem (sapwood) water content in the fifth, downstream position (Eq. 17).
	pc_PositionD1	kJ/m^3	Volumetric heat capacity (pc) in the first, downstream position (Eq. 17 and 18)
	pc_PositionD2	kJ/m^3	Volumetric heat capacity (pc) in the second, downstream position (Eq. 17 and 18)
	pc_PositionD3	kJ/m^3	Volumetric heat capacity (pc) in the third, downstream position (Eq. 17 and 18)
	pc_PositionD4	kJ/m^3	Volumetric heat capacity (pc) in the fourth, downstream position (Eq. 17 and 18)
	pc_PositionD5	kJ/m^3	Volumetric heat capacity (pc) in the fifth, downstream position (Eq. 17 and 18)
	PulseTime	seconds	The length in time of the heat pulse.
	PulseEnergy	J/m	The amount of energy per heat pulse (q in Eq. 18).
C4!	dTmax_PositionD1	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the first downstream measurement position (ΔT_m in Eq. 18).
Maximum temperature rise after heat pulse (ΔT_m in equation 18).	dTmax_PositionD2	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the second downstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionD3	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the third downstream measurement position (ΔT_m in Eq. 18).

	dTmax_PositionD4	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the fourth downstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionD5	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the fifth downstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionU1	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the first upstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionU2	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the second upstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionU3	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the third upstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionU4	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the fourth upstream measurement position (ΔT_m in Eq. 18).
	dTmax_PositionU5	°C	Maximum temperature after the heat pulse minus ambient temperature pre-heat pulse at the fifth upstream measurement position (ΔT_m in Eq. 18).
C5!	SapFlowTotal_SRFM	L/hr	Total sap flow via slow rates of flow method (Eq. 16f).
Total sap flow and sap flux density estimated via slow rates of flow method (heat ratio) (equations 10, 14, 15)	SFD__SRFM_Position1	$cm^3/cm^2/hr$	Sap flux density via slow rates of flow method at the first measurement position (Eqs. 10, 14, 15).
	SFD__SRFM_Position2	$cm^3/cm^2/hr$	Sap flux density via slow rates of flow method at the second measurement position (Eqs. 10, 14, 15).
	SFD__SRFM_Position3	$cm^3/cm^2/hr$	Sap flux density via slow rates of flow method at the third

			measurement position (Eqs. 10, 14, 15).
	SFD__SRFM_Position4	$cm^3/cm^2/hr$	Sap flux density via slow rates of flow method at the fourth measurement position (Eqs. 10, 14, 15).
	SFD__SRFM_Position5	$cm^3/cm^2/hr$	Sap flux density via slow rates of flow method at the fifth measurement position (Eqs. 10, 14, 15).
C6!	SapFlowTotal_Tmax	L/hr	Total sap flow via Tmax method (Eq. 16f).
Total sap flow and sap flux density estimated via Tmax method (equations 13, 14, 15)	SFD__Tmax_Position1	$cm^3/cm^2/hr$	Sap flux density via Tmax method at the first measurement position (Eqs. 13, 14, 15).
	SFD__Tmax _Position2	$cm^3/cm^2/hr$	Sap flux density via Tmax method at the second measurement position (Eqs. 13, 14, 15).
	SFD__Tmax _Position3	$cm^3/cm^2/hr$	Sap flux density via Tmax method at the third measurement position (Eqs. 13, 14, 15).
	SFD__Tmax _Position4	$cm^3/cm^2/hr$	Sap flux density via Tmax method at the fourth measurement position (Eqs. 13, 14, 15).
	SFD__Tmax_Position5	$cm^3/cm^2/hr$	Sap flux density via Tmax method at the fifth measurement position (Eqs. 13, 14, 15).
C7!	StemTemp_PositionD1	°C	Stem temperature at the first downstream measurement position.
Ambient stem temperature prior to the heat pulse.	StemTemp_PositionD2	°C	Stem temperature at the second downstream measurement position.
	StemTemp_PositionD3	°C	Stem temperature at the third downstream measurement position.
	StemTemp_PositionD4	°C	Stem temperature at the fourth downstream measurement position.
	StemTemp_PositionD5	°C	Stem temperature at the fifth downstream measurement position.
	StemTemp_PositionU1	°C	Stem temperature at the first upstream measurement position.
	StemTemp_PositionU2	°C	Stem temperature at the second upstream measurement position.

	StemTemp_PositionU3	°C	Stem temperature at the third upstream measurement position.
	StemTemp_PositionU4	°C	Stem temperature at the fourth upstream measurement position.
	StemTemp_PositionU5	°C	Stem temperature at the fifth upstream measurement position.
C9!	StemTemp_PositionD1	°C	Stem temperature at the first downstream measurement position.
Instantaneous stem temperature.	StemTemp_PositionD2	°C	Stem temperature at the second downstream measurement position.
	StemTemp_PositionD3	°C	Stem temperature at the third downstream measurement position.
	StemTemp_PositionD4	°C	Stem temperature at the fourth downstream measurement position.
	StemTemp_PositionD5	°C	Stem temperature at the fifth downstream measurement position.
	StemTemp_PositionU1	°C	Stem temperature at the first upstream measurement position.
	StemTemp_PositionU2	°C	Stem temperature at the second upstream measurement position.
	StemTemp_PositionU3	°C	Stem temperature at the third upstream measurement position.
	StemTemp_PositionU4	°C	Stem temperature at the fourth upstream measurement position.
	StemTemp_PositionU5	°C	Stem temperature at the fifth upstream measurement position.
X Commands:			
TDD	Trunk Diameter	cm	The diameter of the trunk or stem at site of sensor installation. Default value: 10 cm.
BDD	Bark Depth	cm	Bark thickness at site of sensor installation. Default value: 0.5 cm.
SDD	Sapwood Depth	cm	Sapwood depth at site of sensor installation. Default value: 2.5 cm.
DDW	Density of Dry Wood	g/cm^3	Gravimetric, or specific, wood density. Default value: 0.7 g/cm^3 (ρ_d in Eq. 15 and 17).
TDF	Thermal Diffusivity	cm^2/s	Sapwood thermal diffusivity (Eq. 3). Default value: 0.0025 cm^2/s.
BMD	Baseline temperature measurement duration	seconds	The duration to find the average temperature prior to the heat pulse. Default value: 10 seconds.
HTD	Heat Pulse Duration	seconds	The duration of the heat pulse. NOTE: altering the duration may

			damage the heater element and the plant. It is not recommended to change this parameter. Default value: 3 seconds.
PMS	Post-heat temperature measurement start	seconds	The amount of time after the heat pulse to commence post-heat pulse temperature measurements. Default value: 60 seconds.
PMD	Post-heat temperature measurement duration	seconds	The duration to find the average temperature after the heat pulse. Default value: 20 seconds.
TMD	Maximum temperature measurement duration	seconds	The amount of time after the heat pulse to find Tmax. Default value: 120 seconds.
PRS	Probe spacing	cm	The distance between the heater and downstream or upstream temperature needle. Default value: 0.8 cm.
CDW	Specific heat capacity of dry wood	J/kg/K	Sapwood heat capacity (Eq. 15 and 17). Default value: 1200.

Programming

The Implexx Sap Flow Sensor Gen 2 is an SDI-12 enabled device and will connect to any data logger that supports the SDI-12 protocol. Implexx Sense assumes the user has some familiarity with the SDI-12 protocol and the basics of data logger programming. Implexx Sense strongly recommends contacting the manufacturer of your data logger for further assistance with programs.

Several example programs are available on the Implexx Sense website:

https://www.implexx.io/manuals-and-guides/

Maintenance

Regular Inspection

Implexx recommends inspecting the IX-SF60 sap flow sensor at least every three months, and no less frequently than every six months, to ensure the integrity of the installation. This is particularly important in large trees, where natural wood growth, expansion, and warping may cause the sensor needles to bend, shift, or become embedded in the wood, potentially complicating removal.

To inspect the sensor:

1. Carefully remove or slide the IX-SF60 probes from the stainless steel sleeves embedded in the tree. The probes should come out smoothly with minimal resistance.
2. If necessary, use a flat-bladed tool—such as a flathead screwdriver or chisel—to gently lever the probes from the tree. For guidance, refer to this instructional video: https://www.youtube.com/watch?v=FxIJ3iFw7XI
3. Once the probes are removed, use the sleeve insertion tool to clean and inspect the stainless steel sleeves. The tool should slide in and out of the sleeves with ease.

- If the probes and sleeves are in good condition and removal was effortless, reapply thermal grease to the probes and reinstall them into the existing sleeves. Schedule the next inspection in three months.
- If removal was difficult, or if the insertion tool did not move freely, a new installation site is recommended. Reusing a compromised installation may damage the sensor or yield inaccurate data. When in doubt, prioritize sensor integrity by creating a fresh installation.

Reinstallation Due to Wound Response

The Implexx Sap Flow Sensor Gen 2 should be reinstalled at least once every 12 months. Reinstallation is necessary because plants respond to foreign objects with a wound response, which over time may alter sap flow dynamics and reduce measurement accuracy. Additionally, tree growth can lead to probe misalignment.

In some cases, a pronounced wound response may be observed, including callus formation around the sensor site. In such instances, carefully remove the sensor and install it at a new location.

Recalibration

No recalibration is required for the Implexx Sap Flow Sensor Gen 2. The sensor maintains accuracy for sap flow, sap flux density, and stem water content measurements without recalibration.

Cleaning

Organic material may accumulate on the stainless-steel probes or the white enclosure due to plant exudates. While this generally does not affect sensor performance, the sensor can be cleaned using a non-abrasive wipe and mild soapy water.

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Contact & Support

Implexx Sense, Melbourne, Australia

www.implexx.io

info@implexx.io

PO BOX 285, Moorabbin, Victoria, 3189, Australia