SFM1 Sap Flow Meter Manual

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1   SFM1 Sap Flow Meter Manual

This manual is written to describe the complete operation and installation of the ICT International SFM1 Sap Flow Meter.

NOTE 1: This manual is best used in conjunction with the instructional videos provided on the ICT International YouTube channel: https://www.youtube.com/c/ICTinternational

1.1   Intellectual Property

The specific principle of operation of the Heat Ratio Method (HRM) remains the intellectual property of the publishing authors (Burgess, S.S.O. et al. 2001 *An improved heat pulse method to measure low and reverse rates of sap flow in woody plants.* Tree Physiology 21: 589-598).
The original needle design remains the intellectual property of University of Western Australia (UWA) and the individual developers (Dr Stephen Burgess and Dr Tim Bleby).
The SFM1 Trade Mark is the property of ICT International Pty Ltd. The complete SFM1 Sap Flow Meter remains the intellectual property of ICT International Pty Ltd and incorporates the HRM principle made under exclusive license by ICT International Pty Ltd.

1.2   SFM1 Start Up Check List

WARNING 1 - Please complete this checklist before unpacking the SFM1 Sap Flow Meter.

o   Have you watched the instructional videos? www.youtube.com/c/ICTinternational
o   Have you contacted ICT to schedule training?
      Email: sales@ictinternational.com Phone: + 61-26772 6770

2   System Requirements

2.1   Hardware

The ICT Combined Instrument Software (CIS) does not require a powerful computer. Recommended Minimum System Specifications:
Intel Atom 1.66 GHz and 1GB RAM or higher.

2.2   Software

CIS is compatible with the following Operating Systems:

- Windows 7
- Windows 8.1
- Windows 10
- Windows Virtual OS run from a Mac computer
- MacOS X 10.10 +

2.3   Screen Resolution

CIS works best on current model laptops that have a screen size of 11.6" or larger and/or a native screen resolution of 1366 x 768 or larger.

NOTE 2: ICT Combined Instrument Software requires Microsoft C++ Redistributable 2010. This is available from: https://www.microsoft.com/en-au/download/details.aspx?id=5555

3   Bibliography

3.1   Essential Reading

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3.2   Highly recommended reading

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4   Quick Start Guide

NOTE 3: This manual includes hyperlinks to instructional videos to complement each major section for both practical operation and software function. These videos are located on the ICT YouTube channel: https://www.youtube.com/c/ICTinternational.

4.1   Charge the SFM1 Internal Battery

The SFM1 is a self-contained instrument that incorporates a lithium polymer battery. Before using the instrument, this battery MUST be charged. To choose from a range of charging options see Connecting a Power Supply to the Instrument.

NOTE 4: A unique power-bus plug design was developed by ICT to simplify the electrical wiring process. It minimises the need for custom tools in the field requiring only that the outer cable sheath be stripped back to expose the copper wire.

4.2   Install the SFM1 Software & USB Driver

Insert the supplied USB drive into the computer. On Windows, run SFM1.exe and choose install software. On Mac, open the Combined Instrument Software folder and install the .dmg file.

4.3   Turn the Instrument On

The SFM1 can either be turned on manually by pressing the power button (see - Turn the Instrument On) or automatically by connecting an external power supply (see – Charging the Instrument).

4.4 Connect to the Instrument

Connect the USB cable to the instrument. The SFM1 will automatically be detected by the computer, the same as any USB device. Open ICT Combined Instrument Software and Search for Devices. See section Communications - Connect to the Instrument for details.

4.5 Perform a Verification Test

Before installing or commencing a large field campaign it is recommended that a performance verification test be conducted on the SFM1 Sap Flow Meter. This is best done using the Test Block (SFM-TB) which is designed to return a known sap velocity.

4.6 Install the Sap Flow Meter

Installation of a SFM1 Sap Flow Meter should not be done quickly. Care must be taken in the preparation of the stem surface to remove loose fibrous bark to provide a reference point to work from. The depth of bark and sap wood thickness must be determined to enable correct placement of the measurement needles in the tree. Finally, drilling must be done slowly and carefully to ensure straight parallel holes are produced to prevent measurement error. See Install the Sap Flow Meter for details.

4.7 Set the Logging Interval

The SFM1 Sap Flow Meter has a recommended minimum logging resolution of 10 minutes. This limit is imposed by the thermodynamics of heat movement through a woody matrix. After inputting a pulse of heat into the stem, it must be allowed time to dissipate before applying another pulse of heat. Failure to do so may result in an accumulation of heat in the stem that will introduce error into your results.

NOTE 5: Additional (more frequent) logging intervals are provided for researchers who wish to specifically investigate the time interval required for heat dissipation in specific species, under specific conditions at different Pulse Energy settings. See Measurement Control for details.

4.8 Download Data

Data can be downloaded in a number of ways. The simplest is to click the Download button in the data tab. Data can be downloaded to a specific location in Manage SD. Alternatively, the MicroSD card can be physically removed and read by a computer. See Download Data for details.

4.9 Analyse Data

Data can be saved in either a Comma Separated Values (*.CSV) file format in Sap Flow Reporting Option or a Binary (*.BIN) file format in Needle Temperature reporting mode. Both file formats are supported in the SFT Sap Flow Tool Software that was specifically designed and developed for data analysis, processing and interpretation of Heat Ratio and Heat Field Deformation Sap Flow Data. ICT recommends SFT software for in-depth Sap Flow Data analysis.
ICT Combined Instrument Software cannot use the *.BIN files produced with Needle Temperature reporting mode.

5   Sap Flow Meter Description

The SFM1 Sap Flow Meter consists of: a set of three (3) measurement needles and an integrated, standalone data logger with software for instrument configuration and data downloading. A solar panel can be directly connected to the non-polarised charging ports to charge the internal battery for continuous field operation. The SFM1 has an integrated proprietary 2.4GHz radio transceiver for wireless two-way communications with the ICT International Telemetry Hub or the MCC-Mini.

Photo 1: SFM1 Sap Flow Meter.

5.1 SFM1 Needle Set

The SFM1 measurement needles are made from surgical grade Stainless Steel with an outside diameter of 1.3 mm. The thermistors are positioned exactly 7.5mm and 22.5 mm from the tip of the measurement needles.

Photo 2: SFM1 Measurement Needle Set installed in a small diameter woody stem.

5.1.1 Measurement Resolution

The SFM1 Sap Flow Meter sensor uses a 16-bit microprocessor with 24-Bit Analogue to Digital Converter (ADC). This means temperature measurements are recorded with a 0.001°C resolution. The superior resolution of the SFM1 has significantly improved the accuracy of the original analogue HRM design by removing significant levels of electrical interference and noise from the measured data.

This was demonstrated in the study: Eller, C.B., Pereira, C.G., Oliveira, R.S., Downey, A.M., Burgess, S.S.O., (2012) **Differences in Sap Flow Data Quality between a Thermocouple based HRM Sensor and a Newly Specialised HRM Sap Flow Meter,** Technical Note

5.1.2 Needle Design

All needles are housed in sealed, corrosion-resistant, surgical grade stainless steel needles with high-strength epoxy resin hubs. SFM1 standard needle lengths are 35mm and have two thermistors located 7.5 mm and 22.5 mm from the tip of the needle. This provides a spacing of 15 mm between each measurement point and a 12.5mm distance between the outer measurement point and the epoxy base of the needle. The 15 mm spacing between measurement points is to achieve two discrete readings independent of the thermal sphere of influence of the other. The 12.5 mm spacing from the epoxy base and the outer measurement point allow for varying depths of bark when installing the sensors.

5.1.3 Heater Needle Design

The 35 mm long heater needle consists of a proprietary designed, high resistance filament that dissipates power and yields an exceptionally high and efficient amount of heat. Heaters are designed to be powered by 12 Volts for a period of ~2-8 seconds. As a consequence of the wear and tear associated with repetitive heating and cooling, heater filaments (as is the case with incandescent light bulbs), have a finite and unpredictable life. In this sense, heaters are considered consumables that may require periodic replacement even though the expected lifespan of a heater in constant use in the field is many years. Needle set (heater and temperature needles) replacement should be done by a trained technician certified by ICT International.

WARNING 2 – The measurement needles of the SFM1 can easily be bent, damaged or broken off if basic care is not taken in handling the instrument. If the needles are damaged please contact ICT international via our web site http://www.ictinternational.com/support/rma-form/ and submit a RMA ticket explaining the issue.

5.1.4 Colour coded probes

Each 35 mm long needle is independently attached to the SFM1 Sap Flow Meter by a short, flexible length of cable. Needles are not rigidly fixed to each other to improve the ease of installation. Needle independence allows them to be installed at different distances from the heater so that the Sap Flow Meter can be used to measure sap flow using different Heat Pulse algorithms (such as; HRMx, CHPM or T-Max). Finally, independent needles can be easily replaced in the case of damage or failure. Each needle is colour coded to the specific use (Blue for measurement and Red for heater) and specifically labelled for Top (Downstream) and Bottom (Upstream) to signify the installation position, as orientation of the needles is important.
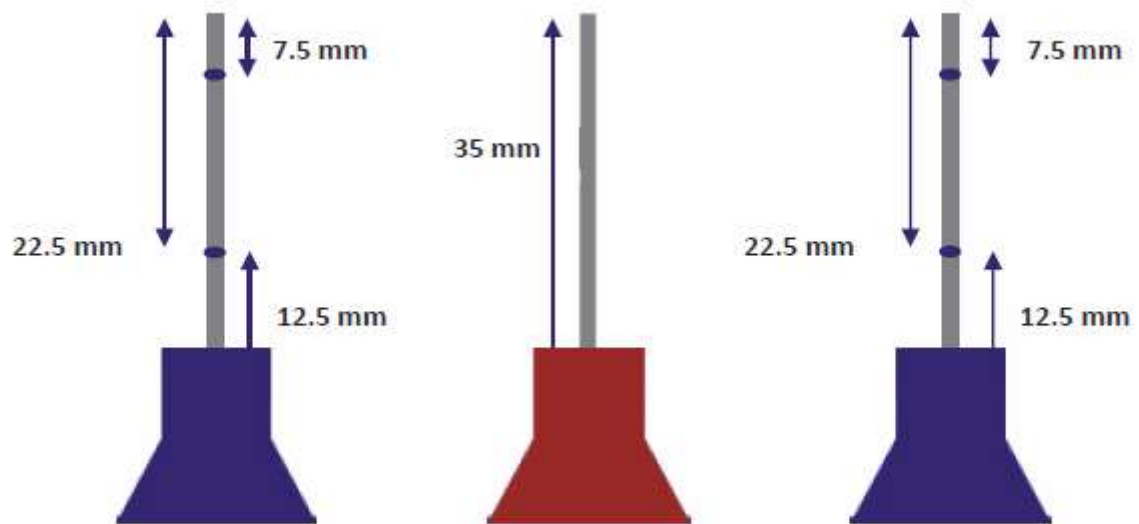
Figure 1: The location of thermistors within the SFM1 needle set.

Photo 3: Colour coded and labelled SFM1 needles.

NOTE 6: It is important to install the needles in the correct order otherwise the sap flow data will be inverted. This is easily identified from analysis of the data as the data will clearly demonstrate a characteristic diurnal sap flow pattern, however, the values will all be negative. This problem is easily fixed by reinserting the needles in the correctly labelled orientation.

5.2   Measurement Reporting Options

The SFM1 Sap Flow Meter can be configured to report the following units:

(1) Needle Temperatures (°C)
(2) Heat Pulse Velocities (cm hr^{-1})
(3) Corrected Sap Velocity (cm hr^{-1})
(4) Corrected Sap Flow (cm^3 hr^{-1})

NOTE 7: Additional configuration information must be known and entered into the SFM1 Sap Flow Meter in order to accurately measure corrected sap velocity (Vs) and sap flow directly. See "Corrections" for details

5.2.1 Needle Temperature

The raw needle temperature mode provides the rawest level of unprocessed data collection. Temperatures for each of the 4 thermistors are logged in °C to allow researchers to manually apply any and all corrections to the data and or process the data using either the HRM or HRMx algorithm. Because no processing of the data is done at the time of collection the raw data can be reprocessed at any time without bias or limitation. This provides researchers the opportunity to revisit, reprocess and reinterpret old data sets in the future as their understanding of plant physiological response develops or thinking changes.

Note that Sap Flow Tool is required for evaluation of Needle Temperature data. Contact ICT International for more information.

5.2.2 Sap Flow Mode

Sap Flow Mode is the default reporting option for the SFM1, recommended for use in most circumstances. This mode uses a default value of thermal diffusivity to calculate the Heat Pulse Velocity. If measured, the actual values can be inputted as Corrections.

5.2.3 Corrected Sap Velocity

Corrected Sap Velocity is a fully processed value that has had corrections made for the specific thermal diffusivity of the plant being measured, wounding corrections made for the response of the plant caused by the insertion of the measurement needle, and any possible asymmetry or divergence of the needles from the theoretical geometry required for the application of the Heat Ratio Method algorithm.
These values must be measured and inputted into the SFM1 Corrections, otherwise default values are used. As some of the correction factors may only be measurable after the SFM1 has been uninstalled, post processing in Sap Flow Tool or ICT Combined Instrument Software is recommended.

5.2.4 Corrected Sap Flow

Corrected Sap Flow is an absolute measure of the volumetric mass flow of water through or within the plant. Due to mechanisms such as hydraulic redistribution, by which plants cope with water or drought stress, the measured sap flow may not be equal to total transpiration through the leaf. It is calculated from the corrected sap velocity by multiplying the sap wood from the annulus surrounding each thermistor and summing them.

5.3   SFM1 Sap Flow Meter

The SFM1 Sap Flow Meter is a standalone instrument, custom designed to specifically measure Sap Velocity and Sap Flow of plants. Each SFM is also a logger with signal processing and integrated power management.

The SFM1 Sap Flow Meter is a highly accurate, high precision microvolt meter. It consists of the needle set (sensor); a microprocessor with 24-Bit ADC that outputs and logs processed data in calibrated engineering units (°C, cm hr^{-1} or Kg hr^{-1}); 4.2V 950 mAh lithium polymer battery; communications via USB, Wireless RF up to 250m line of sight; 4GB MicroSD Card, expandable to 16GB; non-polarised power circuit and dynamic smart charging circuitry, all housed in a waterproof enclosure.

Photo 4: SFM1 Sap Flow Meter Installed on a Pinus radiata tree.

5.3.1 Waterproofing

The custom designed enclosure of the SFM1 has an IP65 rating.
Waterproofing is achieved through a unique physically separated, but electrically linked dual chamber enclosure design. This ensures that the internal circuitry and battery can be electrically linked and charged from an external power supply without providing any physical pathway for water ingress. For this reason, it is important not to open the enclosure because opening the enclosure will void the warranty and water proofing guarantee.

NOTE 8: There is no reason to open the enclosure, the USB Port Cap provides access to all necessary interfaces of the instrument such as USB communication port, MicroSD card and power switch.

WARNING 3 – The instrument is not waterproof if the USB Port Cap is left unscrewed. Water entry via this port is not covered under warranty.

5.3.2 Power Management

The instrument has its own internal 4.2V 950mAh lithium-polymer battery. It also features a nonpolarized power circuit; internal voltage regulation; a 12V transformer to drive the Heat Pulse and optical-isolation based surge protection.

5.3.3 External power

External power can be supplied with a DC voltage supply from either a 22W solar panel or a 24V power supply. See Powering - Charging the Instrument for specific details and charging options.

5.3.4 Tools

No specialised tools are required for the connection of the power supply or installation of instruments. External power is connected through the non-polarised power-bus ports of the instrument utilising a unique bare wire, push fit connection mechanism. See Individual Power Supply Connections for details. The needles of the SFM1 are permanently fixed to the instrument with a custom water proofing gland and should only be removed for repair by a qualified technician.

5.3.5 Power Fail Safe Mode

In the event that power is lost due to insufficient sun, such as extended monsoonal cloudy conditions, the logger will enter hibernation mode. When the internal battery is recharged, the instrument will reactivate and recommence logging at the preconfigured intervals without human intervention. Data is not recorded whilst the logger is in hibernation, but no data collected prior to hibernation will be lost. Data is permanently stored in non-volatile memory on the MicroSD card.

5.3.6 Electrical Surge Protection

Surge protection is accomplished through optical isolation, interrupts and barriers designed into the circuitry of the instrument. These are designed to prevent electrical discharge from destroying the instrument. This is an important protection feature against electrical discharge, but it will not prevent damage and complete destruction from a direct lightning strike on the instrument.

5.3.7 Data Storage & Memory

Data is stored on a 4GB MicroSD card (included). Larger capacity MicroSD cards (up to 16GB) can be used if required. The theoretical capacity of the standard 4GB MicroSD card is approximately 443 years when all parameters are logged at a 10 minute temporal interval.

5.3.8 Communication

Communication with the instrument can be made using a standard Mini-USB cable and a computer running Windows or Mac. Alternatively, every instrument includes a 2.4 GHz transceiver for wireless communication. Wireless communication up to a distance of 250m (line of sight) can be achieved when using a MCC-Mini with the standard antenna. Wireless connection allows for the same configuration and data download capabilities as a USB cable.

5.3.9 Software & Firmware

Software and firmware updates are available from the ICT web site:
http://www.ictinternational.com/support/software/

ICT Combined Instrument Software automatically checks for updates.

Firmware updates require the Device Firmware Updater (DFU) software (available free from the link above). The process usually takes less than 10 minutes.

NOTE 9: When updating firmware, be sure that the instrument is charged before attempting the update. Loss of power may cause the firmware to become corrupted. The instrument will not allow a firmware update unless the internal battery voltage of the instrument is above 3.8V.

5.3.10 Operating Temperature Range

Operating range is between 80°C and -40°C, however we recommend that the instrument be kept below 50°C where possible. A minimum temperature of -40°C is possible due to the incorporation of heaters built under the microprocessor chips to warm them to the minimum operating temperature for silicon chips and microprocessors.

NOTE 10: Whilst the instrument can operate at these extreme temperatures (80°C to -40°C), it is unlikely that the plant will.

6 Heat Ratio Method Theory

The Heat Ratio Method (HRM) can measure both sap velocity (V_s) and volumetric water flow in xylem tissue using a short pulse of heat as a tracer. It is a modification of the Compensation Heat Pulse Method. By measuring the ratio of heat transported between two symmetrically placed temperature sensors, the magnitude and direction of water flux can be calculated.
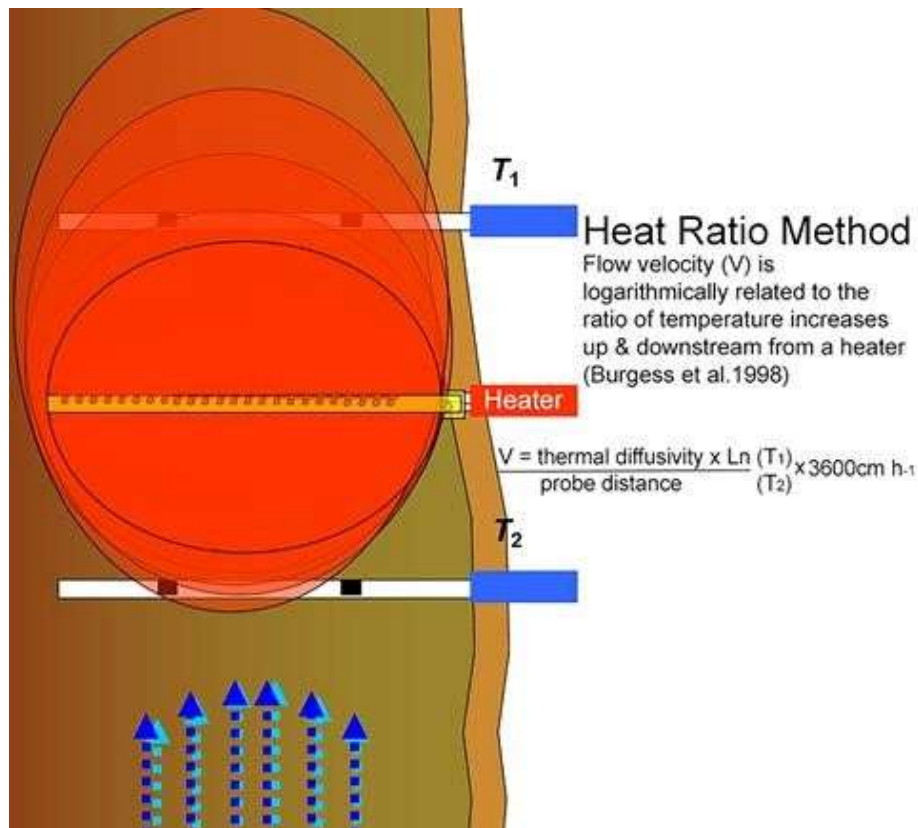
Figure 2: Heat Ratio Method principle.

This method was developed by the University of Western Australia and partner organisations ICRAF and CSIRO. The SFM1 Sap Flow Meter has been validated against gravimetric measurements of transpiration and used in sap flow research since 1996. (Burgess et al. 2001).
The SFM1 can be used on lignified or woody stems greater than 10mm in diameter without any maximum diameter limit. It can also be successfully used on hollow stemmed plants such as bamboo. Because of the invasive nature of this method, HRM may not be suited for use on herbaceous crop plants (although trials with Sugar Cane, banana and Maize have demonstrated very good results).

The operator can choose to report data output in raw temperature mode, Heat Pulse Velocity, Sap Velocities, or Sap Flow. The last two options eliminate most of the need to post process data. The SFM1 is capable of measuring accurately between 100 to -100 cm hr^{-1} covering a very wide range of plant species and environmental conditions that produce high, low, zero and reverse rates of sap flow.

NOTE 11: The expected heat pulse velocities of the majority of plant species in most environments will be < 60 cm hr^{-1} for conventional (acropetal) flow and no greater than -5 to -10 cm hr^{-1} reverse (basipetal) flow.

"AN IMPROVED HEAT PULSE METHOD TO MEASURE LOW AND REVERSE RATES OF SAP FLOW IN WOODY PLANTS"

Stephen S.O Burgess, Mark A. Adams, Neil C. Turner, Craig R. Beverly, Chin K. Ong, Ahmed A. Khan and Tim M. Bleby.

6.1 Measurement and calculation of heat pulse velocity

6.1.1 CHPM (Compensation Heat Pulse Method)

For the CHPM, two probes containing temperature sensors are aligned with the axis of a plant stem or root and inserted radially to equal depths in the xylem. A heater element is similarly inserted at a fixed distance upstream from the midpoint between the temperature probes. A common configuration locates the heater 0.5 cm from the upstream temperature probe and 1.0 cm from the downstream probe (here denoted as a –0.5, 0, 1.0 cm configuration). During measurement, wood and sap are heated in pulses and convection through the flowing sap stream carries the heat toward the midpoint between the temperature probes. When both temperature probes have warmed to the same degree, the heat pulse has moved the 0.25 cm from the heater, i.e., to the midpoint between the probes. The time taken for the heat pulse to move this distance is used to calculate heat pulse velocity (V_h):

$$V_h = \frac{x_1 + x_2}{2t_0} 3600 \qquad \text{Equation 1}$$

where: t_0 is time to thermal equilibration of the downstream and upstream probes after release of the heat pulse, and x_1 and x_2 denote distances (cm) between the heater and the downstream and upstream temperature probes, respectively (we use these terms as they apply in the case when water flows from soil to leaves). A negative value is assigned to x_2 because it is located on the opposite side of the heater to x_1.

6.1.2 HRM (Heat Ratio Method)

The HRM measures the ratio of the increase in temperature, following the release of a pulse of heat, at points equidistant downstream and upstream from a line heater. Heat pulse velocity is calculated as (Marshall 1958):

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) 3600 \qquad \text{Equation 2}$$

where: k is thermal diffusivity of green (fresh) wood, x is distance (cm) between the heater and either temperature probe, and v_1 and v_2 are increases in temperature (from initial temperatures) at equidistant points downstream and upstream, respectively, x cm from the heater. The probe positions relative to the heater used with the HRM are –0.6 and 0.6 cm, hence x = 0.6 cm. Thermal diffusivity (k) is assigned a nominal value of 2.5 x10^{-3} cm^2 s^{-1} (Marshall 1958) and this value is further resolved once sapwood properties have been measured (see below).

6.2   Theory: Influence of measurement time

Marshall (1958) stated that the v_1/v_2 ratio remains constant with time, rendering the time of measurement unimportant; however, Marshall's (1958) description did not account for departures from the ideal state that can arise from two sources. **First:** patterns of heat transfer are altered by blocking of, and damage to, xylem vessels caused by insertion of probes. Additional disruption of heat transfer occurs because the thermal properties of the sensor material (e.g., stainless steel) differ from those of xylem. **Second**: even with careful probe placement, it is likely that probe spacing will be at least slightly asymmetrical. Both of these departures from the ideal cause v_1/v_2 to change with time with the result that measurement time affects results. Ratios of v_1/v_2 will approach an ideal value asymptotically, with the rate of change decaying exponentially with time following the heat pulse (Figure 3).
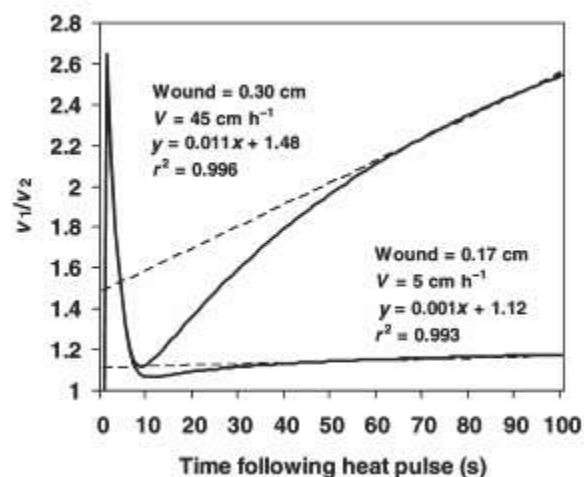
Figure 3: Modelled changes in v_1/v_2 ratios with time for a small wound width (0.17 cm) and low sap velocity (5 cm h^{-1}) compared with a large wound width (0.30 cm) and high sap velocity (45 cm h^{-1}). Note that with both mild and extreme departures from the ideal caused by sensor implantation, v_1/v_2 is essentially linear between 60 and 100s as indicated by the r^2 values for the linear regressions fit over the data for this period.

However, even in the most extreme cases, the rate of change in v_1/v_2 after 60s becomes extremely small and ratios will be effectively linear and have a slope of less than 0.01 (Figure 1). This finding has two important implications. First, measurements should be made at least 60s after the heat pulse has been released. Second, multiple sampling of v_1/v_2 is possible. For example, because our multiplexer cycle speed was 2.8s, we logged and averaged 14 measurements of v_1/v_2 over the period 60–100s to minimize the contribution of any random signal noise to measurements. Because v_1/v_2 is effectively linear between 60 and 100s, the value of these averaged ratios will differ from an "ideal" value measured at the median time of 80s by < 0.4% for extreme cases, although generally this difference will be negligible. Because random variation in v_1/v_2 arising from thermal and electronic interference can contribute an error an order of magnitude greater, multiple sampling of v_1/v_2 is desirable.

6.3   Theory: Correction for probe misalignment

All heat pulse velocity techniques are highly sensitive to errors arising from inaccurate probe spacing. For example, when the CHPM is configured as described earlier, a 1mm error in spacing for either probe will introduce a 20% error in calculations of V_h. With the CHPM, probe misplacement is assessed by placing over-length probes in drill holes and measuring the spacing and angle of the protruding probes (Hatton et al.1995). With the HRM, probe placement is measured in situ, which considers thermal and physical symmetry (e.g., whether thermocouples or thermistors lie symmetrically within the probe housing (Becker 1998)). At $V_h = 0$ (which can be imposed by severing the root or stem), probe spacing is calculated as:

$$x_2 = \sqrt{\left(4kt \ln\left(\frac{v_1}{v_2}\right) + x_1{}^2\right)}$$ Equation 3

Where: x_2 denotes the incorrectly spaced probe, x1 is assumed to be correctly spaced at 0.6 cm and t is measurement time (Equation 1). Because time has an essentially linear effect on Equation 3 over 60–100s, it can be solved by using the median measurement time (80s) or by averaging solutions calculated for each t value used in the measurement series. Results of the two approaches differ by < 1% in extreme cases. Once calculated, x1 and x2 values can be derived with Equation 3, and corrected Vh calculated as (adapted from Marshall 1958):

$$V_h = \frac{4kt \ln\left(\frac{v_1}{v_2}\right) - (x_2{}^2) + (x_1{}^2)}{2t(x_1 - x_2)} 3600$$ Equation 4

By correcting a small sample of data and comparing uncorrected values with corrected values, a simple linear relationship can be derived that can be used to correct the remaining data.

As it is not known which probe is incorrectly positioned, our approach was to also solve Equations 3 and 4 assuming x_1 is incorrectly positioned and then average the two solutions to yield an intermediate solution (Burgess et al. 1998). Use of this intermediate solution prevents biasing corrections of sap flow in either direction. Results for the two extreme scenarios differ from the intermediate solution by ± 4 to 22% for moderate (0.05 cm) to extreme (0.3 cm) positioning errors, respectively (see Figure 2B), indicating that large errors in probe placement cannot be corrected with sufficient certainty and these cases should probably be abandoned. Examples of the effects of a large spacing error on measurements, the correction procedure and its results are shown in Figures 2A and 2B.
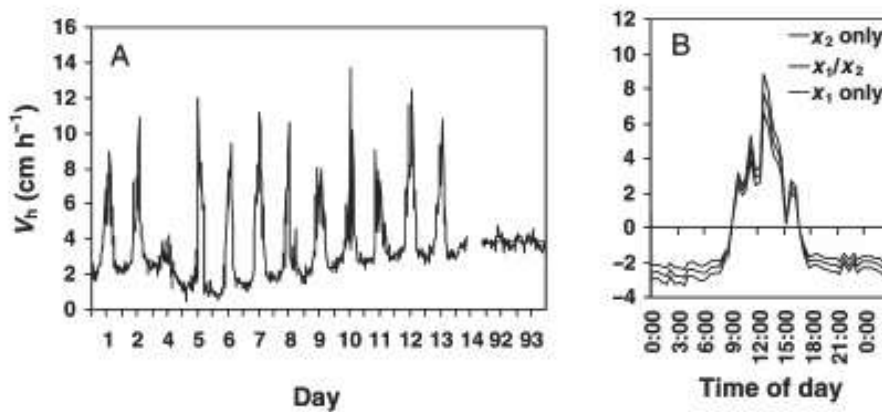
Figure 4: (A) Example of an episode of reverse flow (hourly means) in a lateral root of *Eucalyptus camaldulensis Dehnh*, erroneously measured by probes with a large spacing error (~0.2 cm). Data on Days 92 and 93 were collected after the root was severed to stop flow and indicate the potential for ambient temperature fluctuations to disturb measurements in uninsulated sensors. The straight line shows the mean erroneous velocity arising from a probe spacing error.

6.4   Theory: Correction for wounding

Installing sensors in xylem tissue causes substantial mechanical damage. In addition to the interruption of flow pathways by the insertion of the probes, intact vessels may become occluded as the plant responds to wounding by forming tyloses (Barrett et al. 1995). The resulting region of non-conducting wood around the site of probe insertion affects measurement of V_h by decreasing v_1/v_2. Swanson and Whitfield (1981) used a finite-difference numerical model to produce a simple algebraic equation for wound correction. The model calculates three coefficients (a, b and c, for varying wound widths) to calculate corrected heat pulse velocity (V_c) measured with the CHPM according to:

$$V_c = a + bV_h + cV_h{}^2 \qquad\qquad\qquad\qquad\qquad\text{Equation 5}$$

Swanson (1983) also generated a limited number of coefficients for symmetric probe configurations such as the HRM. Unfortunately, as with the coefficients for the CHPM, Swanson's (1983) solutions do not pass through the origin and the resulting corrections yield a poor approximation of low, zero and reverse rates of sap flow. We therefore developed a new numerical model to supply appropriate wound correction coefficients. To correct heat pulse velocity measured with the HRM, three coefficients: b, c and d are used in Equation 6:

$$V_c = bV_h + cV_h{}^2 + dV_h{}^3 \qquad\qquad\qquad\qquad\text{Equation 6}$$

6.5   Determining sap velocity

Only a portion of xylem tissue (the xylem lumen) contains moving sap. Heat pulse probes effectively measure a weighted average of the velocities of moving sap and "stationary" wood (Marshall 1958). Sap velocity can be determined on a real basis by measuring the fractions of sap and wood in xylem and accounting for their differing densities and specific heat capacities. Barrett et al. (1995) modified Marshall's (1958) equation relating V_c to sap velocity (V_s) as:

$$V_s = \frac{V_c p_b (c_w + m_c c_s)}{p_s c_s} \qquad\qquad\qquad\qquad\text{Equation 7}$$

Where: ρ_b is the basic density of wood (dry weight/green volume), c_w and c_s are specific heat capacity of the wood matrix (1200J kg^{-1} °C^{-1} at 20°C (Becker and Edwards 1999)) and sap (water, 4182J kg^{-1} °C^{-1} at 20°C (Lide 1992)), respectively, m_c is water content of sapwood and ρ_s is the density of water.

6.6 Converting sap velocity to sap flow

Volumetric flow can readily be derived as the product of sap velocity (V_s) and cross-sectional area of conducting sapwood. Gross wood cross-sectional area is calculated from its under-bark radius. Heartwood area is discounted by staining the sapwood (Goldstein et al. 1998) or by observing the dark colour often associated with heartwood. Where sap velocity (V_s) is estimated at several radial depths, total sapwood area is divided into concentric annuli delimited by the midpoints between measurement depths. In this way, point estimates of sap velocity (V_s) are weighted according to the amount of conducting sapwood in the annulus they sample.

7   Measurement Cycle and Process

The measurement cycle is outlined below:

Measurement cycle initiated
(at set time intervals, e.g. every 10 minutes)

↓

Acquire an 80 second average of the initial temperature of each individual thermistor

↓

Initial sapwood temperature measured and averaged (mV outputs from the thermistors are measured and converted to temperature in °C)

↓

Heat pulse released
(An exact power input in Joules is supplied via the instruments microprocessor)

↓

Increases in sapwood temperature measured, compared and averaged
(Between 60 to 100 seconds, begin summing Δ temperature for thermistors down and upstream from the heater to obtain the average ratio of downstream temperature increase to upstream temperature increase {see Equation 8 below})

↓

Mathematical calculations performed on downstream/upstream temperature ratios (the natural log of the ratio of temperature increase is used to calculate heat pulse velocity by multiplying it by thermal diffusivity (k), dividing by the distance (x) between either one of the needles and the heater and converting this value to cm hr^{-1} by multiplying by 3600)

↓

Measurements are stored on the MicroSD card as either: needle temperatures, raw heat pulse velocity, corrected sap velocity (V_s) or sap flow.

The integrated microprocessor of the SFM1 implements the measurement cycle outlined above. The exact algorithm for the Heat Ratio Method automatically performed by the microprocessor is outlined as follows:

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) x 3600 \text{ cm h}^{-1} \qquad\qquad \text{Equation 8}$$

Where: k is the thermal diffusivity of wet wood, x the distance between the heat source (heater) and temperature sensors, and v_1 and v_2 are the increases in temperature (from ambient) at equidistant points downstream and upstream, respectively, x cm from the heater.

8   Powering - Charging the instrument

The SFM1 is a stand-alone instrument designed for long term deployment in remote areas for continuous, unattended logging applications. Each instrument has an internal 4.2V (950mAh) lithium polymer, rechargeable battery. The microprocessor is a sophisticated low power chip and the instrument operates between 4.2V to 3.6V, using on average only 3.5 mA in idle state. An integrated transformer provides the 12V supply required to fire the measurement Heat Pulse at the required energy level in Joules as configured by the operator in ICT CIS.

At the heart of the instrument is a very sophisticated charging circuit that features a non-polarised, two-wire power-bus. This eliminates the chance of damaging the electronics by incorrect wiring of the positive and negative terminals from an external power supply. A purpose designed and built internal charging regulator regulates supplied voltages between 8-30V DC, preventing overcharging of the internal battery to ensure a long service life.

NOTE 12: ICT recommends the use of 22W solar panels for most applications; or 24V DC mains power supplies for greenhouse/lab applications.

8.1 Power Requirements

Power status is monitored, controlled and logged by the SFM1 instrument. The SFM1 is designed for low power usage, with a sophisticated microprocessor-controlled power supply circuit.

8.1.1 Idle State Power Consumption

In the idle state, between heat pulses, the current consumption is only 25mA continuous. During a measurement cycle this rises to 45 mA for approx. 120 seconds, with a peak consumption of 670 mA for a maximum of eight seconds during the firing of the heat pulse.

8.1.2 Communications Power Consumption

Communicating to the SFM1 via USB or radio uses approximately 65 mA continuously during communication; however, the SFM1 will be charged via USB whilst connected. The total power consumption depends on the frequency and duration of communications.

8.1.3 Heater Power Consumption

SFM1 heater filaments are manufactured to strict specifications and all have resistances of exactly 18.0 ohms. The microprocessor of the SFM1 can precisely control the amount of current flowing through the heater circuit to achieve the exact pulse energy in Joules as configured by the operator, see Pulse Energy for details. This means that all SFM1 Sap Flow Meters perform identically and should a heater need replacing, it can be replaced without any change to the instruments performance.

NOTE 13: The HRM principle, a ratio method, is not sensitive to the absolute amount of heat released. The measurement is based on the ratio of the temperature rise of each symmetrically placed measurement point in the stem.

The heaters use approximately 8 watts of power when active (12 V @ 667 mA through an 18 Ohm resistor/heater). The heat pulse delivered by the heater is typically on for approximately 2.5 seconds every 30 minutes, so average power use by the heaters is only 8x2.5/(1800) = 11 mWh.

NOTE 14: All Heat Pulses are generated from the internal battery regardless of any external power source that may be connected.

8.2 External Power Supply Options

When the SFM1 is connected to an external power supply, basic instrument functions are powered directly from the power source, bypassing the internal battery, with the exception of the measurement heat pulse. The measurement Heat Pulse is always supplied directly from the internal battery to ensure continuous supply from a regulated stable power source for the very high instantaneous current required for the heat pulse. The internal 4.2 V lithium battery of the SFM1 is trickle charged by the external power supply to maintain its full charge.

8.2.1 External Battery-Only Power Supply

Note: **Continuous connection of an external battery or constant power supply (for days to months at a time) is not recommended as this can shorten the life of the internal battery. ICT International recommend using a solar panel directly connected (with no external battery backup in parallel) wherever possible; or a timer switch to turn off external power for 8-12 hours daily to simulate a solar panel during the day and night.**

It is possible to operate the SFM1 at hourly logging intervals on 20 Joule pulses for approx. 24 hours using only the instruments own internal battery. Whilst convenient, this is of minimal practical use for long term field deployments. A small 7 Ah external battery can operate the SFM1 (at 10-minute temporal logging and 20 Joule pulses) for up to seven (7) days before needing to be recharged or exchanged for a fully charged external battery.
See Appendix O: SFM1 External Battery Operation Test (without Solar Panel).
However, ICT International recommends the use of a solar panel instead of an external battery wherever possible.

NOTE 15: The SFM1 internal battery provides a unique advantage in that external power supplies can be disconnected and exchanged without losing power to the instrument. This prevents disruption to logging and avoids the need to reconfigure the instrument should it be necessary to adjust or change external power supplies.

In circumstances where a solar panel is not viable, 85 Ah to 100 Ah sealed, lead gel acid, deep cycle batteries **may be used in conjunction with a timer switch**. Deep cycle batteries are recommended because they are specifically designed to handle successive charge and discharge cycles without damage. Sealed lead gel acid batteries are preferable to standard wet cell batteries because they do not require maintenance or refilling with water. Wet cell batteries can be used but are susceptible to spillage when transporting to the field and can lose electrolyte rapidly during summer conditions. They will also not have the same service life as a deep cycle battery and will require more regular replacement.

NOTE 16: ICT does not supply 12V batteries because the shipping & dangerous goods costs to do so are prohibitive. ICT recommends that where multiple SFM1 are daisy chained to a single battery (or battery bank) all batteries used (either wet cell or deep cycle) should have a minimum current rating of 85 Ah. ICT also recommends the use of a battery box. This is a plastic enclosure typically custom moulded to fit a large battery that will protect the battery from environmental elements that will cause a reduced service life and supply problems. Ask your battery supplier for details.

8.2.2 Solar Power Supply

ICT International recommends the use of solar panels as the power supply for all non-laboratory-based instruments.
A solar panel can be connected directly to the Sap Flow Meter via the non-polarised two wire power-bus, using the unique power bus-plugs on either side of the instrument. The SFM1 does not

need a solar regulator when using it with a solar panel. Please see the schematic <u>Connecting Power directly via a solar panel</u>, and the <u>Solar Panels</u> section for determining the correct solar panel capacity for your research.

WARNING 4 - When connecting power to the SFM1, use the bus-plugs on either the top (with the antenna and needles), or the bottom. Do not split the power input with on one input top and bottom on the same side of the instrument. The gold-plated pipes run the entire length of the instrument on each side. Placing a positive and a negative input into the same pipe (top and bottom of the instrument) will cause a short circuit.

8.3 Extension cables

Because the SFM1 regulates and trickle charges the internal battery, low impedance, expensive extension cable is not required. A common, low cost (and readily available) "figure-8" or "lamp cord" cable is all that is required and can be used over long distances and cut to size as required to connect an external power supply and/or daisy chain multiple devices together to share a single external power supply.

NOTE 17: the outer diameter of the insulating sheath of each conductor core of the "figure-8" or "lamp cord" cable should be no greater than 3 mm.

9   Connecting a Power Supply to the Instrument

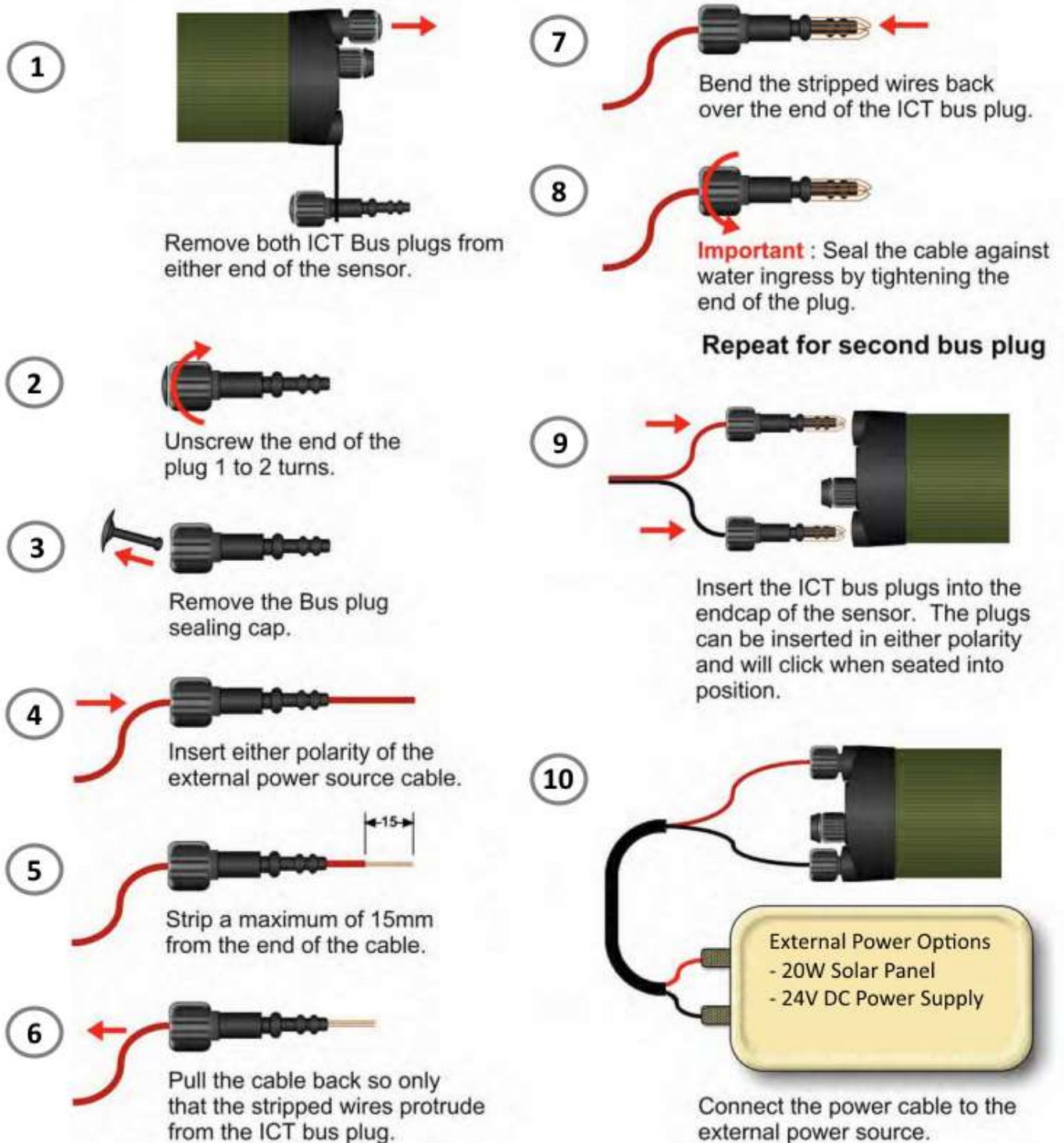Important: Do not connect external power until the final step

1 Remove both ICT Bus plugs from either end of the sensor.

2 Unscrew the end of the plug 1 to 2 turns.

3 Remove the Bus plug sealing cap.

4 Insert either polarity of the external power source cable.

5 Strip a maximum of 15mm from the end of the cable.

6 Pull the cable back so only that the stripped wires protrude from the ICT bus plug.

7 Bend the stripped wires back over the end of the ICT bus plug.

8 Important : Seal the cable against water ingress by tightening the end of the plug.

Repeat for second bus plug

9 Insert the ICT bus plugs into the endcap of the sensor. The plugs can be inserted in either polarity and will click when seated into position.

10
External Power Options
- 20W Solar Panel
- 24V DC Power Supply

Connect the power cable to the external power source.

Figure 5: Using the unique ICT Bus Plugs to charge the SFM1 internal battery.

The unique power bus-plug design was developed by ICT International to simplify the electrical wiring process. It minimises the need for custom tools in the field requiring only that the outer cable sheath be stripped back to expose the copper wire. No other tools are required with all necessary components and fixings fully incorporated into the instrument design. Retaining straps ensure the power-bus plugs do not separate from the instrument when removed from the power-bus during wiring preparation and connection of external power.

Powering and charging the instrument is very easy and there are several different options to choose from, providing flexibility in experimental design to suit your specific situation:

- Direct low-rate via USB[1]
- Direct via Solar Panel
- Daisy-chaining instruments to share a power supply.

The following diagrams illustrate the use of the unique power bus-plugs and the different power configuration options that can be used to provide continuous instrument operation and trickle charging of the internal battery for long term deployment.

Note: **Continuous connection of an external battery or constant power supply (for days to months at a time) is not recommended as this can shorten the life of the internal battery. ICT International recommend using a solar panel directly connected (with no external battery backup in parallel) wherever possible; or a timer switch to turn off external power for 8-12 hours daily to simulate a solar panel during the day and night.**

[1] The SFM1 has a variable charge rate of between 60 and 200mA. The USB charge rate is 100mA. Maximum charge rate of 200mA is active when external voltage is above 16 volts DC (Solar Panel or CH24). Time required to fully charge the SFM1 @ 200mA is 3 hours. Time required to fully charge the SFM1 via USB is 6 hours.

9.1 Individual Power Supply Connections

9.1.1 Connecting Power Directly via a USB cable from a Computer

* The USB Port cap should be removed as per Chapter 12.1
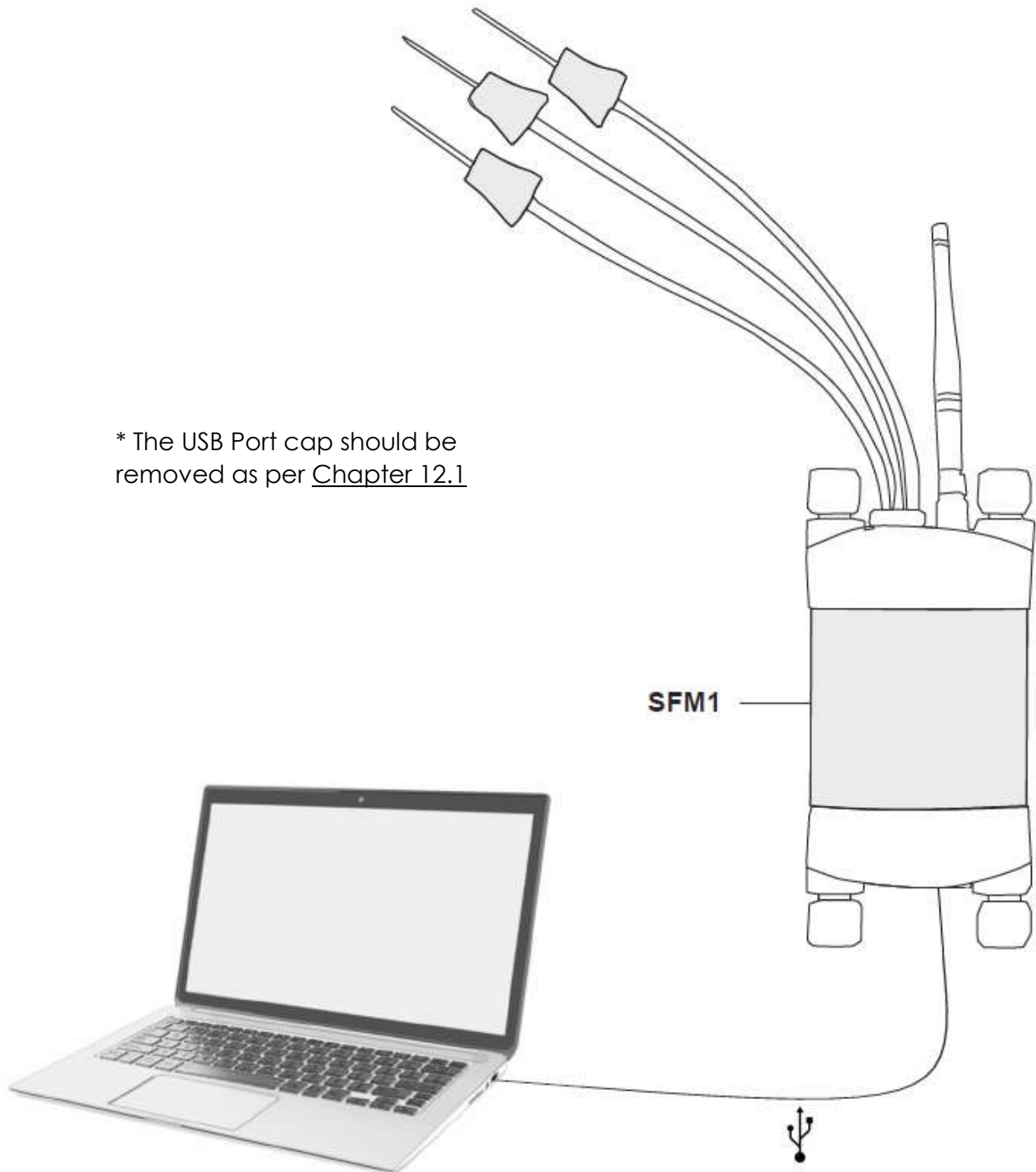
SFM1

9.1.2 Connecting Power Directly via Solar Panel

* The SFM1 Sap Flow Meter
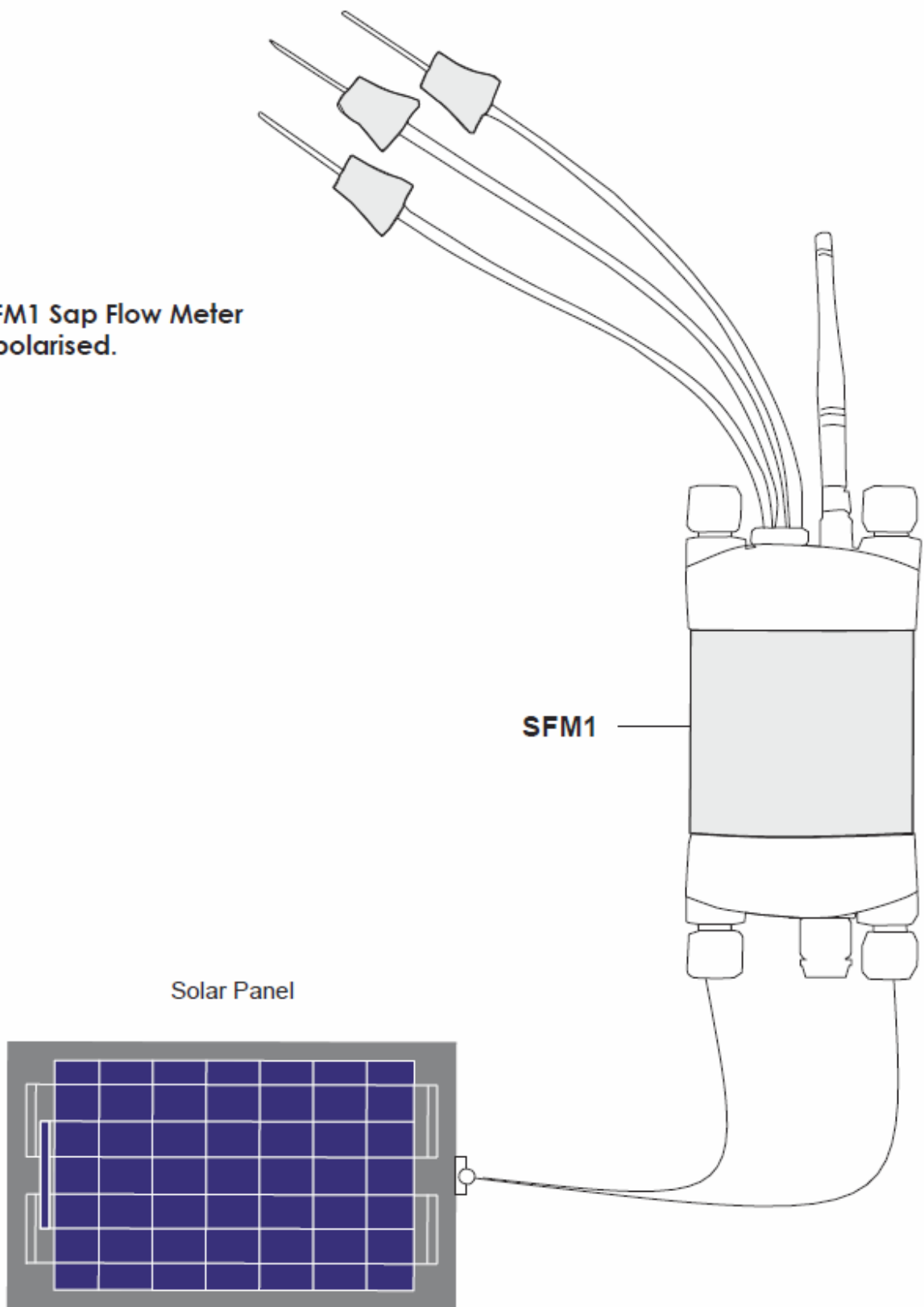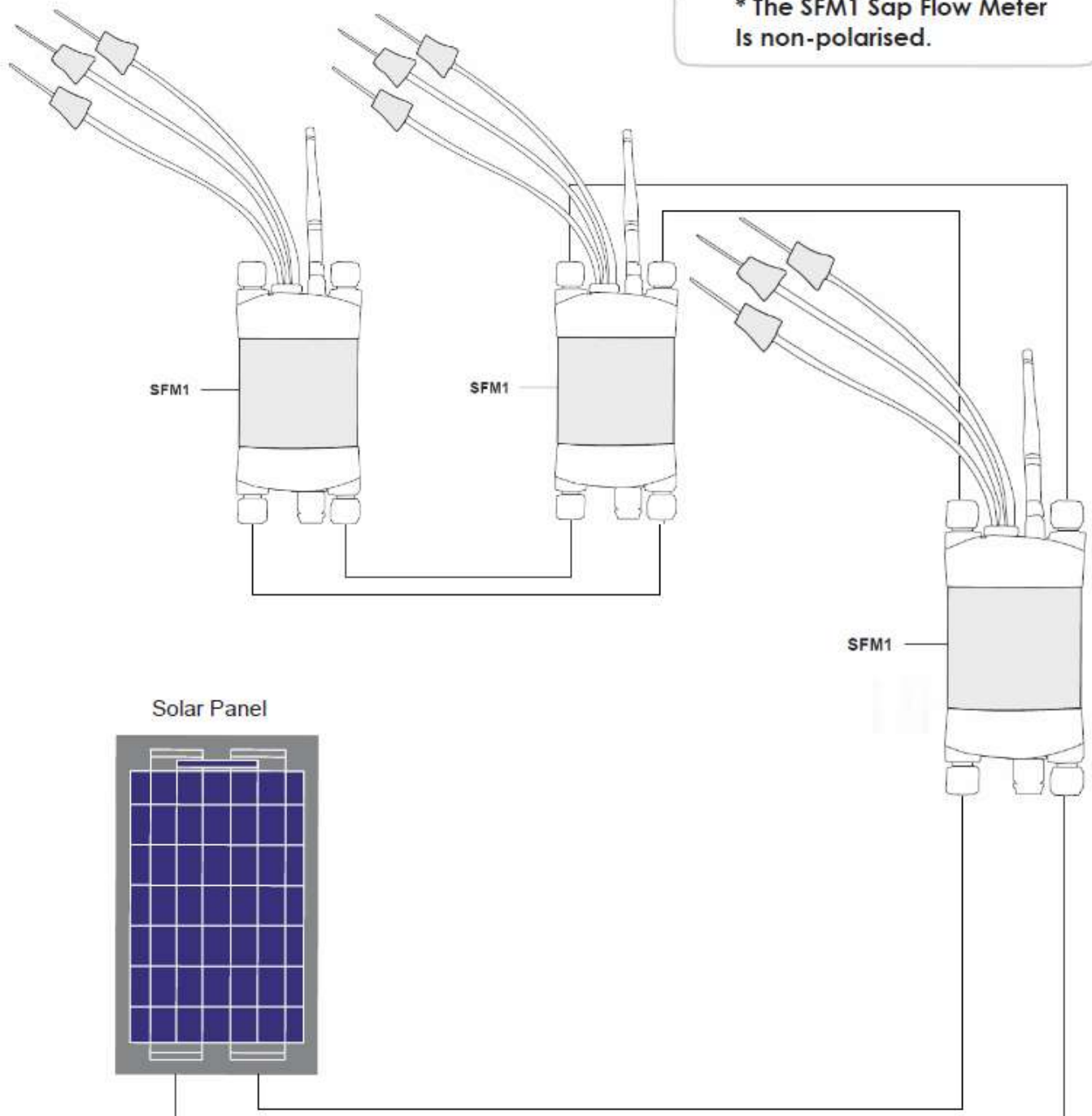is non-polarised.

SFM1

Solar Panel

Figure 6: Solar panel connected directly to a SFM1 Sap Flow Meter

9.1.3 Daisy Chaining with a Solar Panel

* The SFM1 Sap Flow Meter Is non-polarised.

SFM1

SFM1

SFM1

Solar Panel

10   Solar Panels

The SFM1 is designed for long term field deployments, typically in remote locations. The sophisticated power circuit of the instrument is intended to operate independently utilizing a standard 20 Volt/20 Watt solar panel connected direct to the instrument. These solar panels can either be purchased direct from ICT to provide a complete solution at the time of purchase or sourced locally by the end user.

With a solar panel attached, the SFM1 will regulate the charging current from the external source and dynamically trickle charge the internal 4.20 V battery. The output voltage of solar panels varies a great deal depending on the amount of solar radiation striking the surface of the panel. For example, in full sunlight a 20 Volt solar panel will typically supply up to its maximum Vmp of 18Volts, even when the sun is at a low angle. This will result in the SFM1 charging at a maximum rate of 200mA/h. Where partial sun light or diffuse light (shade) strikes the solar panel its output voltage will drop significantly to around 8 to 12 Volts. The internal battery of the SFM1 will still charge, but at a reduced rate, down to as low as only 60 mA/h. The dynamic charging circuit is designed to maximise any and all available light, either direct or diffuse solar radiation, at any time of the day or conditions to ensure maximum possible charge of the battery is achieved.

10.1   Solar Panel Specifications

If sourcing a solar panel locally ICT International recommends the following specifications be matched by your local supplier.

Pmax	20Wp
Vmp	18.00V DC
Imp	1.14A
Voc	22.50V
Isc	1.27A
Maximum System Voltage	1000V
Size	360*540*35mm
Test Condition	AM1.5, 25°C, 1000W/M2

Where:

Pmax = Power Maximum
Vmp = Voltage maximum power - what the Voltage would be under ideal conditions with the maximum output current.
Imp = Amps maximum power. "I" refers to Intensity and is a legacy term used prior to the adoption of the SI unit, Ampere. Imp * Vmp = Solar panel Watts.
Voc = Voltage Open Circuit or nothing is attached to the panel
Isc = Current under short-circuit conditions. The Peak current a solar panel can produce with its output shorted. It is used for calculating wire size and circuit protection ratings.

NOTE 18: ICT recommends the use of Monocrystalline solar panels as they work better in low-light or shaded conditions. Polycrystalline Photovoltaic cells are less expensive but have lower efficiency.

10.2 Solar Panel Calculator

Depending upon the scientific question being asked, the experimental design will inevitably involve a custom configuration of the instrumentation. Typically, the independent operation of the SFM1 with its own solar panel provides greatest flexibility in experimental design and is the optimal configuration. However, in some cases it may be desirable to have a single external power supply servicing a large number of SFM1 Sap Flow Meters or a mixture of instruments and a weather station all located at a single site.

For instruments with high power draw such as the SFM1, ICT International recommends a maximum of 2 instruments per 20W solar panel.

10.3 Solar Panel Mounting

ICT offers a multipurpose Solar Panel Post Mount (SPPM) for mounting of solar panels. The SPPM is specifically designed for mounting the SP22 solar panels. The panels are set at a default 45° angle but can be fully adjusted on the mounting pivot to ensure that the best possible zenith angle to the sun can be achieved to maximise the Equivalent Sun Hours (ESH) for optimum charging.

10.3.1 Mounting on a Star Picket

The Solar Panel is supplied with a mounting kit designed to fit the solar panel onto a standard star picket or steel post. At the base of the mount a locking screw is fitted to prevent the panel rotating on the post.

Photo 5: SP22 Solar Panel mounted to star picket.

Photo 6: Locking screw on base.

The angle of the panel is adjusted to suit the angle of the sun using the wing nut and pivot, as shown below.

Photo 7: Angle Adjustment.

NOTE 19: Solar Panels should always be pointed North in the Southern Hemisphere or South in the Northern Hemisphere.

10.3.2 Mounting Options

The SPPM is designed for mounting on a steel fence post or Star Picket, but can also be attached to larger diameter wooden posts such as Vineyard trellis posts. Alternatively, the upright of the SPPM can simply be dug straight into the soil for autonomous operation. The SPPM can also be attached to a branch of the tree within the canopy to securely install the solar panel at a preferred angle within a well-lit portion of the canopy.

Photo 8: SPPM installed directly in the soil to mount and position a SP22 22W solar panel.

Photo 9: SPPM used on the branch of a tree.

10.4 Connection of Solar Panel to the SFM1

The solar panel connects directly into the power bus ports of the SFM1. No regulator required.

The first step in connection of a panel is to strip the wires to the required length. Remove about 100mm of the outer sheath of the cable (if applicable), then strip the individual conductors (wires) and expose bare copper to a length of approximately 20mm.

Photo 10: Solar panel cable with the insulation stripped to expose the required length for correct installation in the SFM1

WARNING 5 - If connecting the solar panel outdoors in sunlight, do not touch the positive and negative wires together, as this may damage the solar panel.

Remove both power bus plugs from one end of the SFM, loosen the locking nut, and remove the waterproof caps as shown below. A second set of bus plugs are located at the opposite end of the SFM1 so that multiple sap flow meters can be connected together in a daisy chain fashion, running from one solar panel.

Photo 11: Inserting the prepared, stripped solar panel cable into the power-bus plugs at one end of the SFM1.

Insert the wires through the bus-plugs. Push the wire through the plug to allow the bare wire to protrude out the end of the plug. Fold the bare wire back onto the bus plugs and then tighten the nuts. The plugs are ready to insert into the logger to connect the solar panel.

The plugs are a deliberately tight compression fit. The two small O-rings on the tips of each bus-plug are not intended for water proofing. Instead they are to ensure the cable is pressed against the power bus pipes to ensure good electrical connection.

Push the bus plugs into place ensuring that an audible click is heard as the bus-plugs are fully inserted.

NOTE 20: The power bus is designed such that water ingress will not damage the instrument or effect instrument operation in any way.

Photo 12: Inserting the power-bus plugs with stripped cable into the power bus ports on either side of the SFM1

NOTE 21: The small protective Bus Plug caps are not used when wires are inserted.

11 Software & USB Driver Installation

11.1 Instrument Set-up and Configuration

NOTE 22: All changes that you make and confirm by clicking the relevant Update icon will be stored in non-volatile memory. That is, they will be retained even if you turn the power off and on.

11.2 SFM1 Utility Software

NOTE 23: All software described in the proceeding section is included on the USB drive supplied with the instrument.

11.2.1 Installation

A Graphical User Interface (GUI) is used to configure and operate the SFM1 Sap Flow Meter. ICT Combined Instrument Software (CIS) is compatible with Windows and Mac operating systems.

All software is available from: http://www.ictinternational.com/support/software/

a) **Install the USB Driver** (Windows)
b) **Install ICT Combined Instrument Software** by completing the install wizard.
c) If an error occurs when running CIS, install Microsoft C++ 2010 redistributable.
     This is available from: https://www.microsoft.com/en-au/download/details.aspx?id=14632

12   Turning the Instrument On and Off

The Sap Flow Meter has an internal 4.2V 950 mAh Lithium Polymer. The internal battery must be charged from an external power source (such as a Solar Panel) for long term field deployment. The Sap Flow Meter can be turned on manually by pressing the power button or automatically by connecting an external power supply, including a USB cable.

NOTE 24: The SFM1 can also be charged directly from any computer's USB port, USB charger or power bank.

12.1   Turn the SFM1 On

The SFM1 has a physical power button located inside the USB port cap. To access this button, remove the USB port cap by unscrewing the large 'knurled' part.

NOTE 25: the USB port cap consists of two parts (a) the large knurled portion and (b) the smaller Gore-Tex vent. You must unscrew the whole port cap by turning the larger knurled portion.

a) Large 'knurled' part of the USB port cap – Undo this.

b) Gore-Tex Vent – Do not undo this portion separately.
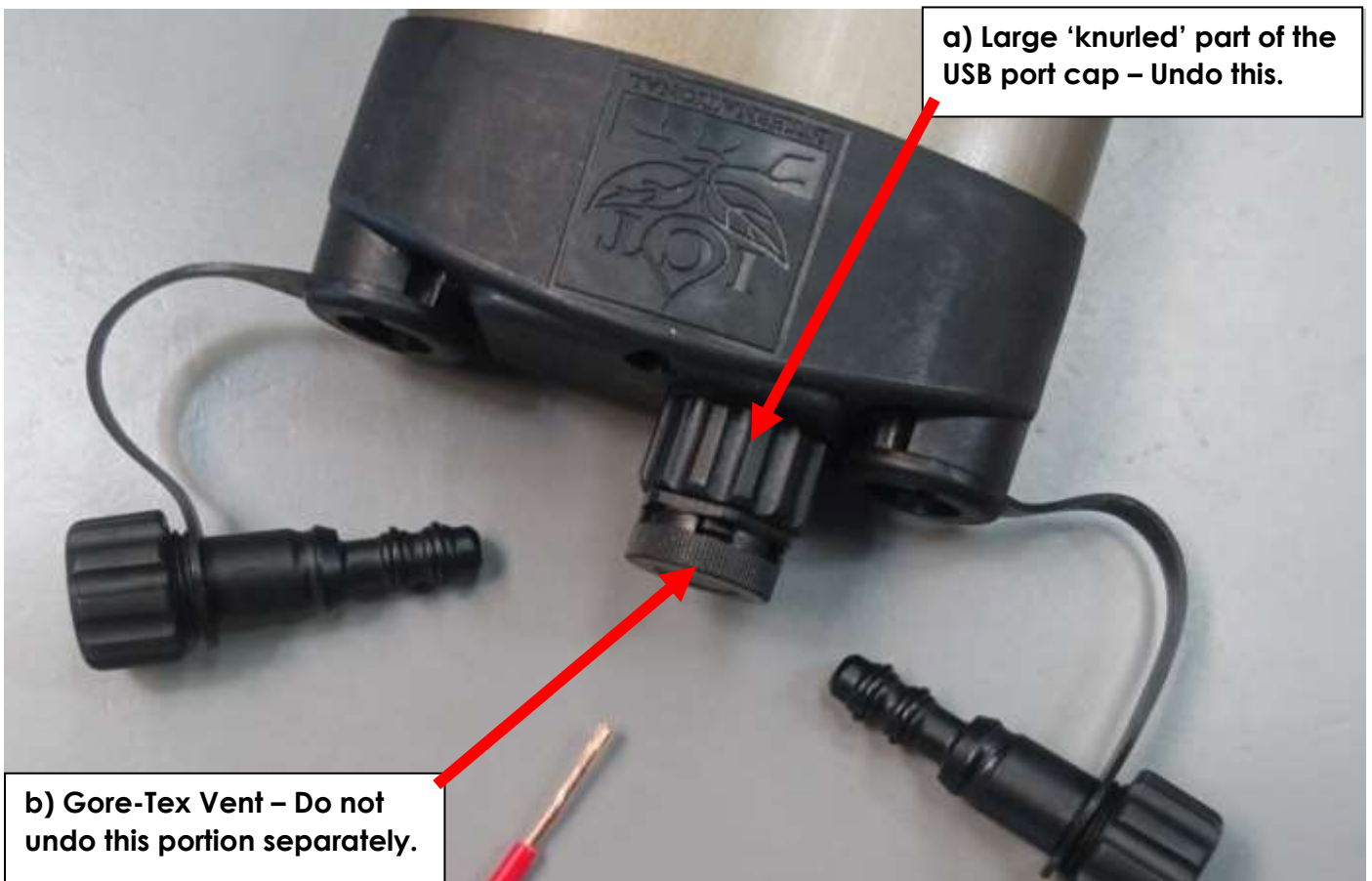
Photo 13: The Power switch is located below the USB port cap.

The power button is located above the USB port. It is a small rectangular grey button.

NOTE 26: In most cases the user should be able to use their finger to press the button. VERY LITTLE force is required to depress the power button. If you find this technique difficult you can use a small screwdriver or tweezers to gently depress the button.

To turn the SFM1 on, press and hold the button for approximately 1 second. When the instrument is turned on, the green LED (visible through the light tube, adjacent to the communication port) will flash rapidly for a few seconds during start up. The LED will remain lit for 10 to 15 seconds before turning off. Once the SFM1 has started the green light will flash once every 10 seconds to indicate it is powered on.
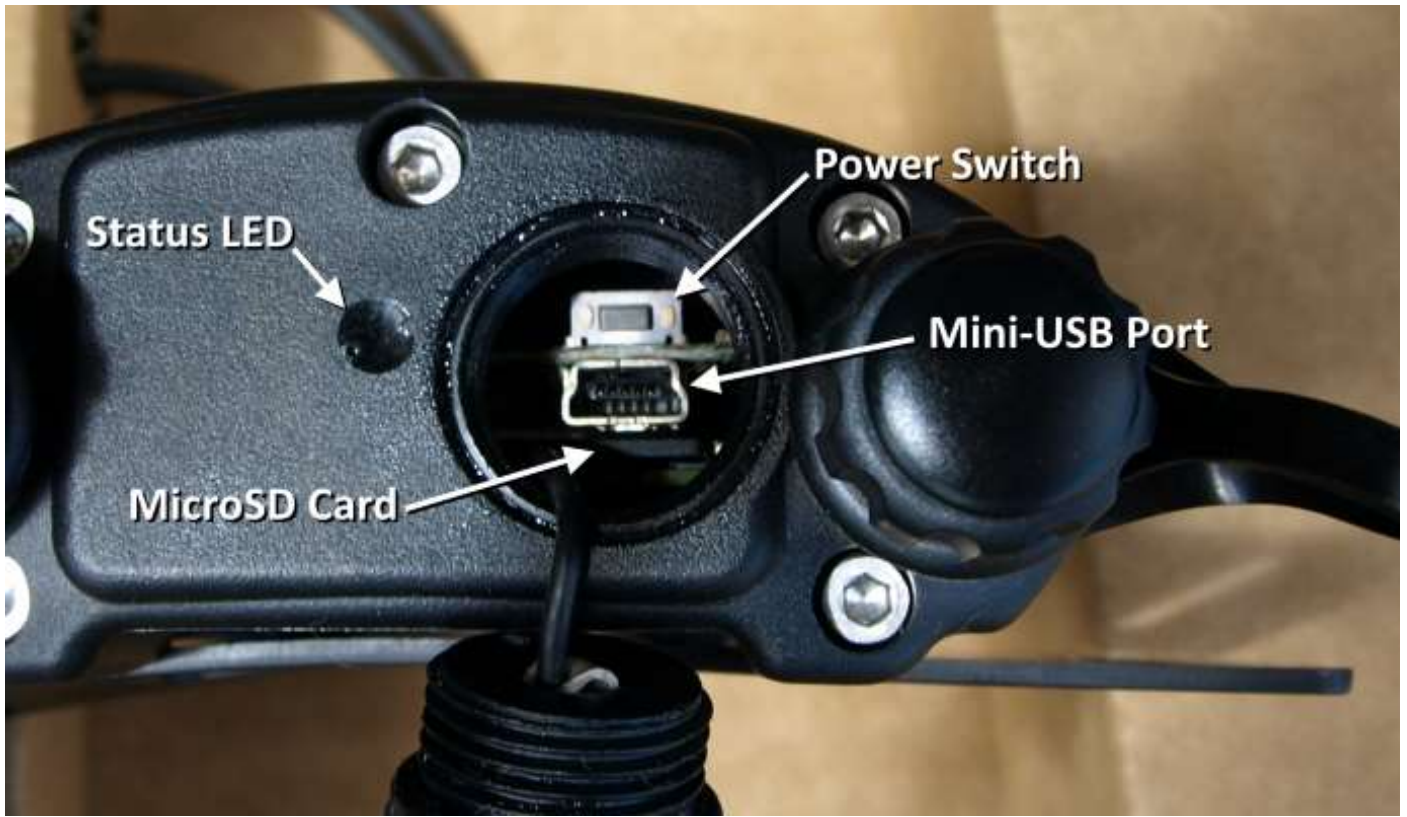
Photo 14: SFM1 USB port access.

12.2   Turn the SFM1 off

The SFM1 does not turn off automatically. If external power is disconnected from the instrument it will continue to operate from the internal battery. It must be turned off manually. This can be done by pressing and holding the power button for 3 seconds. The LED will flash red and green and fade out.

The SFM1 can also be turned off with the Power Down button in the top right of the software.
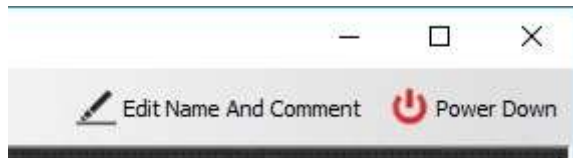
Figure 8: The CIS Menu Bar provides a function to Power Down instruments.

NOTE 27: The SFM1 cannot be turned off whilst connected to external power. Pressing and holding the power switch will just display a Green LED. Using the software will display a warning.
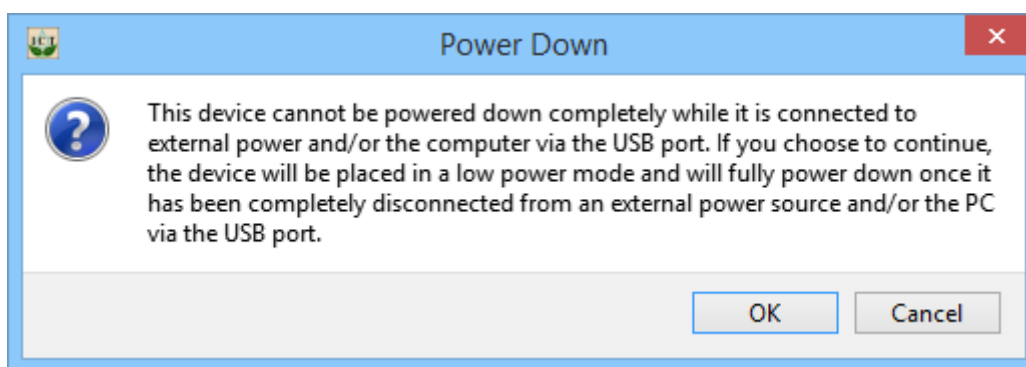
Figure 9: Warning that the SFM1 cannot power down as external power is still connected.

13   Communications

13.1   Connect to the Instrument

After opening the software, connect the instrument to your computer and Search for Devices.
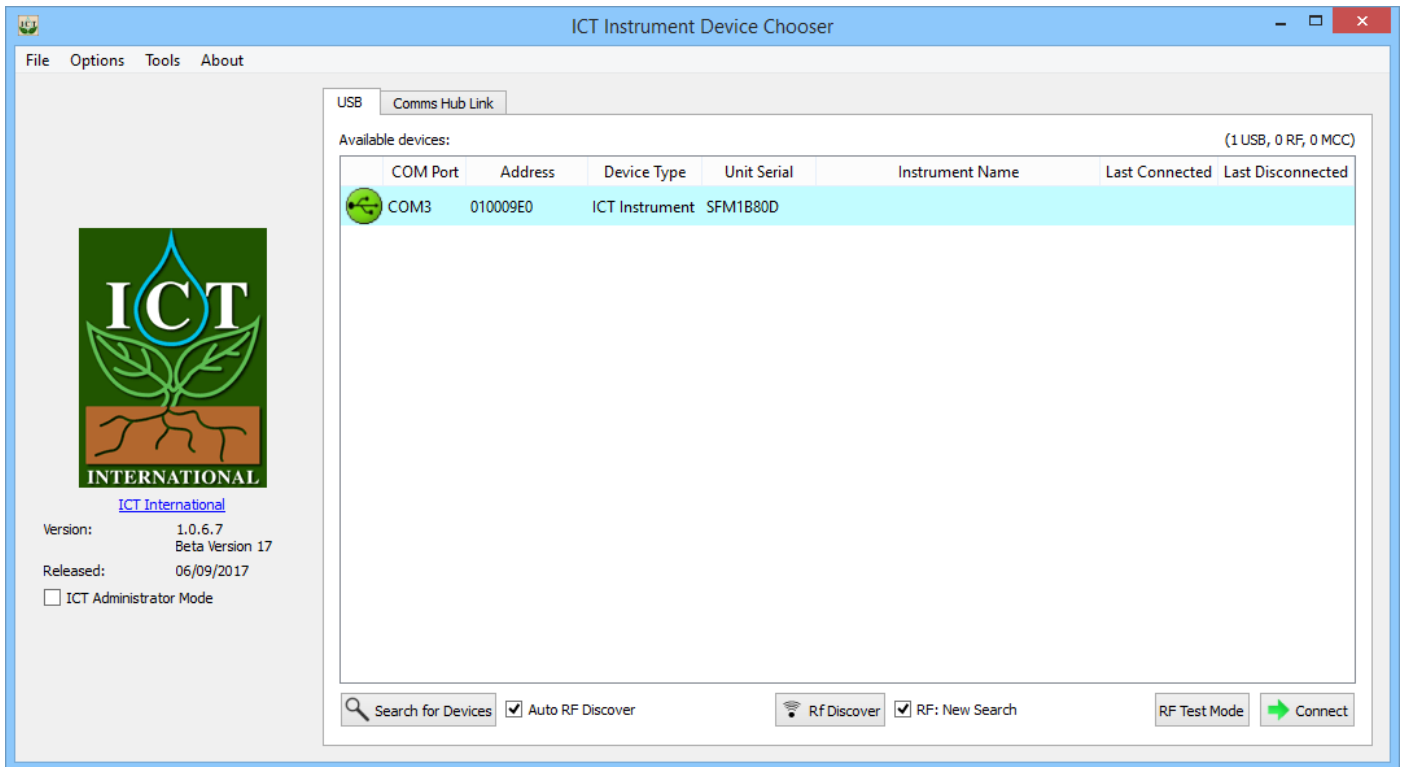
To connect to the instrument, double-click it on the list, or select it and Connect.

Additionally, the ICT CIS Device Chooser displays:

1. The list of discovered instruments
2. Product Version – 1.0.6.7
3. Release Date – 06/09/17

Other functions include:

Check for Software Updates.
Access to additional data visualisation (contact ICT).
Wireless instrument discovery (Requires MCC).
Wireless (RF) signal strength test (Requires MCC).
Remote instrument configuration (Comms Hub Link – Requires Telemetry Hub).
Telemetry Hub Account Management.

13.2 Wireless Connection

To connect to an instrument wirelessly, you need a MCC-Mini or an ICT Telemetry Hub.

Connect the MCC-Mini/Hub to your computer and Search for Devices, making sure the Auto RF Discover option is selected.

Connection is otherwise the same as via USB.

13.3 Disconnecting

To disconnect from the instrument without turning it off, simply close the software.

14   LED Status Indicators

The instrument has a red and green LED programmed to give specific flash sequences to indicate different states of operation of the instrument.

The LEDs are connected to the power circuit and are located under the light tube adjacent to the USB port cap. They indicate if the instrument is on and if the battery is charging.

A green flash every 10 seconds indicates that the device is on.

A red light indicates that device battery is charging.

14.1   Device Firmware

When using the Device Firmware Updater software (DFU) to update the application board, the red LED will continuously blink. The board should not be powered down while the red LED is blinking.

While performing updates of the generic comms board, the LEDs should be off, but could be in any state as they are not being controlled.

14.2   Power down

When the power button is pushed, either a Green LED or Red LED will blink while you are holding the power button. If the Green LED blinks the board will not switch off when you let go of the power button. This is most likely because it is powered externally, and cannot shut down.
If the Red LED blinks, the board is ready to be powered down. Letting go of the power button will start the power down sequence, which will result in both LEDs blinking and fading out until the board is off.

NOTE 28: If power is applied to the external inputs during the power down sequence, power down is aborted and the unit will reinitialise.

15   Instrument Configuration

Configuring the SFM1 Sap Flow Meter is a very straight forward process, performed using a simple GUI. Configuration consists of allocating the instrument a recognisable name and comment that relates to the specific purpose of the experiment and differentiates it from the next Sap Flow Meter, setting the date & time, choosing a reporting option, setting a heat pulse energy level, and choosing a logging interval.

The software is based around 4 tabs:

Channels – this tab displays the current state of the instrument and the measurement.

Data – for downloading and managing data on the instrument.

Configuration – to set up logging.

Information – Detailed information about the instrument and component serial numbers.
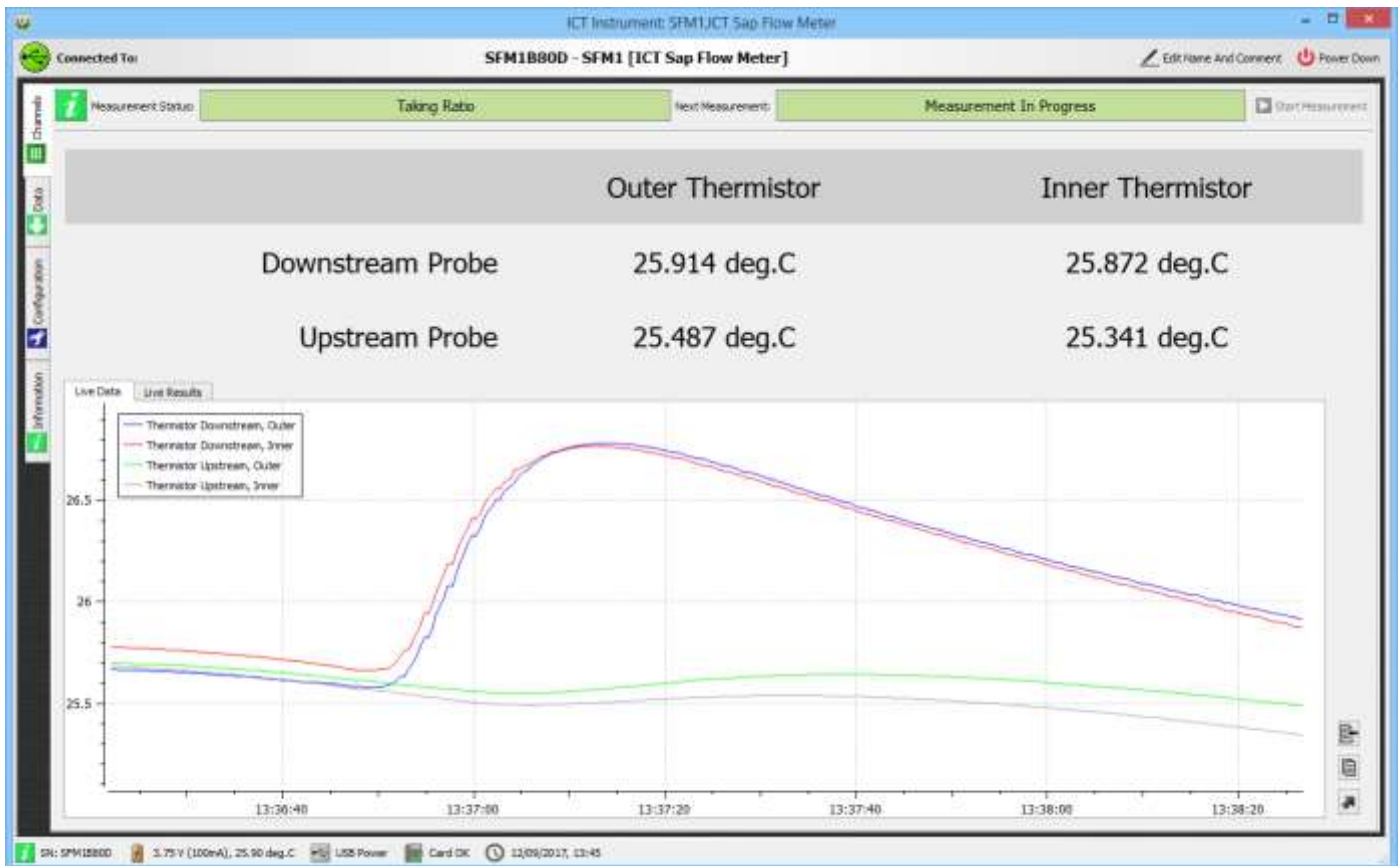
Figure 10: The Channels tab of CIS when connected to a SFM1.

15.1   Name and Comment

The name and comment should be indicative of the instrument or treatment and identify its location. The name and serial number are displayed in the discovery list, this is particularly useful when connecting wirelessly.

15.2   Instrument Status

The instrument serial number, battery voltage, charge status, MicroSD card status and the current instrument time is displayed along the bottom of the software.

15.3 MicroSD Card

If Card OK is displayed at the bottom of CIS then the card is working normally.
Other statuses that can be displayed are:

No Card Inserted – No card has been detected by the instrument.

Card Error – The MicroSD card is incorrectly formatted or corrupted. This can usually be fixed by reformatting the card as FAT/FAT32 (this is the default in Windows).

15.4 Serial Number

The serial number is used automatically as the 8-character data file name. When using the instrument for the first time or inserting a new MicroSD card, upon making the first measurement, a data file is automatically created using the serial number as the file name with a .csv extension. Once downloaded to a PC the file name can be changed, but data can only be saved to the SD card in this file name format. This serial number is also stored in the header line of the data file. The serial number is used for technical support purposes by ICT technicians.

15.5 Configuration

15.5.1 Measurement Mode

The Heat Ratio Method is based around using a pulse of heat as a tracer to measure the flow of water through the water conducting xylem or sapwood of a plant.

Firing a heat pulse whilst heat from a previous pulse is still present will affect the measurement results. Under normal conditions it takes about 5-10 minutes after each pulse for the effects of the pulse to dissipate completely such that plant tissues have cooled to match the ambient temperature. 10 minutes is adequate time for the heat to move through the system, and as such is the minimum recommended logging interval.

Shorter logging intervals are possible, however anything below 10 minutes is purely for academic research and testing purposes and is not recommended for field deployment. Other typical logging intervals such as 15, 20, 30 and 60 minutes are available from the drop-down box. In the majority of cases these intervals are well matched to the speed at which plants change in response to environmental conditions and therefore provide sufficient detail on plant function.
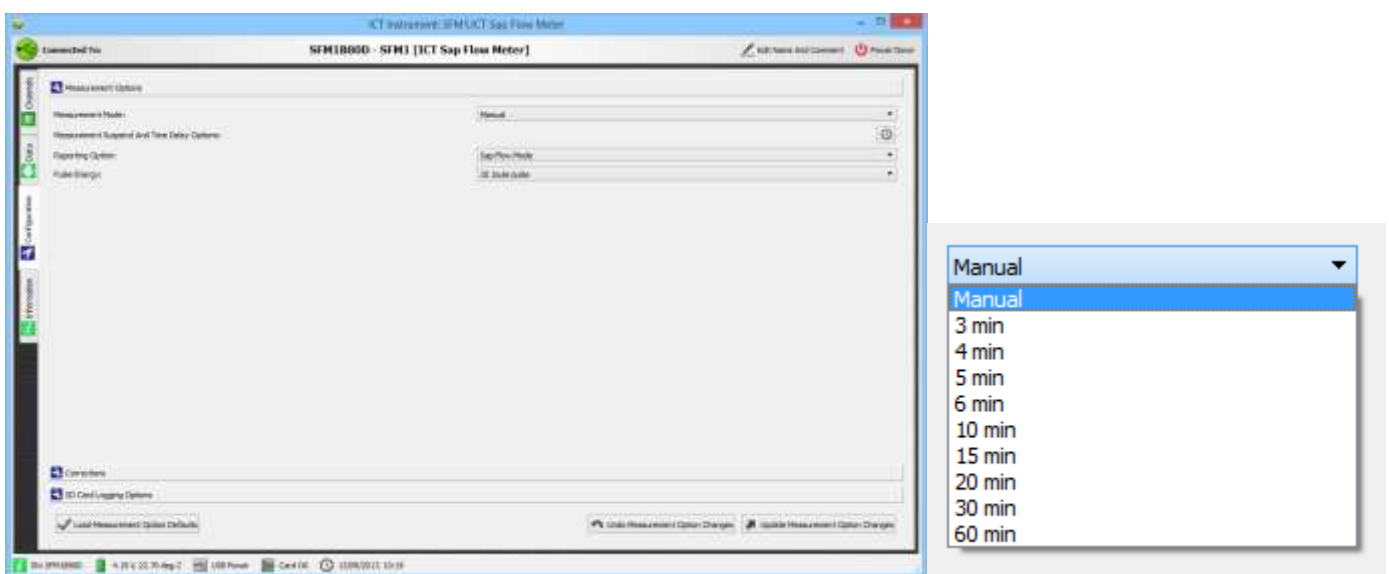
Figure 11: Measurement Mode dropdown and available logging intervals.

15.5.1.1 Manual

In manual mode, the user can use the Start Measurement button on the Channels tab to initialise a measurement at any point. This is useful for testing the SFM prior to installation in the field, or taking a measurement to check installation. With the SFM in Manual mode the software will display the measurement progress and results.

WARNING 6 - DO NOT PULSE WHEN NEEDLES ARE IN AIR. Making a measurement with the heater needle in air may damage the heater element.

The manual measurement mode is convenient for testing instrument operation and performing a test of the needles prior to deployment in the field. A test can be conducted by placing the needles of the SFM1 into the sleeves as labelled on the SFM Test Block. Note that the sleeves are not symmetrical around the heater, this layout combined with the use of a compound of known thermal properties is how the Test Block has been designed to produce a known sap velocity when a measurement is made.

Place the SFM1 in Manual mode and Start a Measurement. The software will display the effect of the Heat Pulse, causing the temperature of the downstream then upstream sensors to rise.
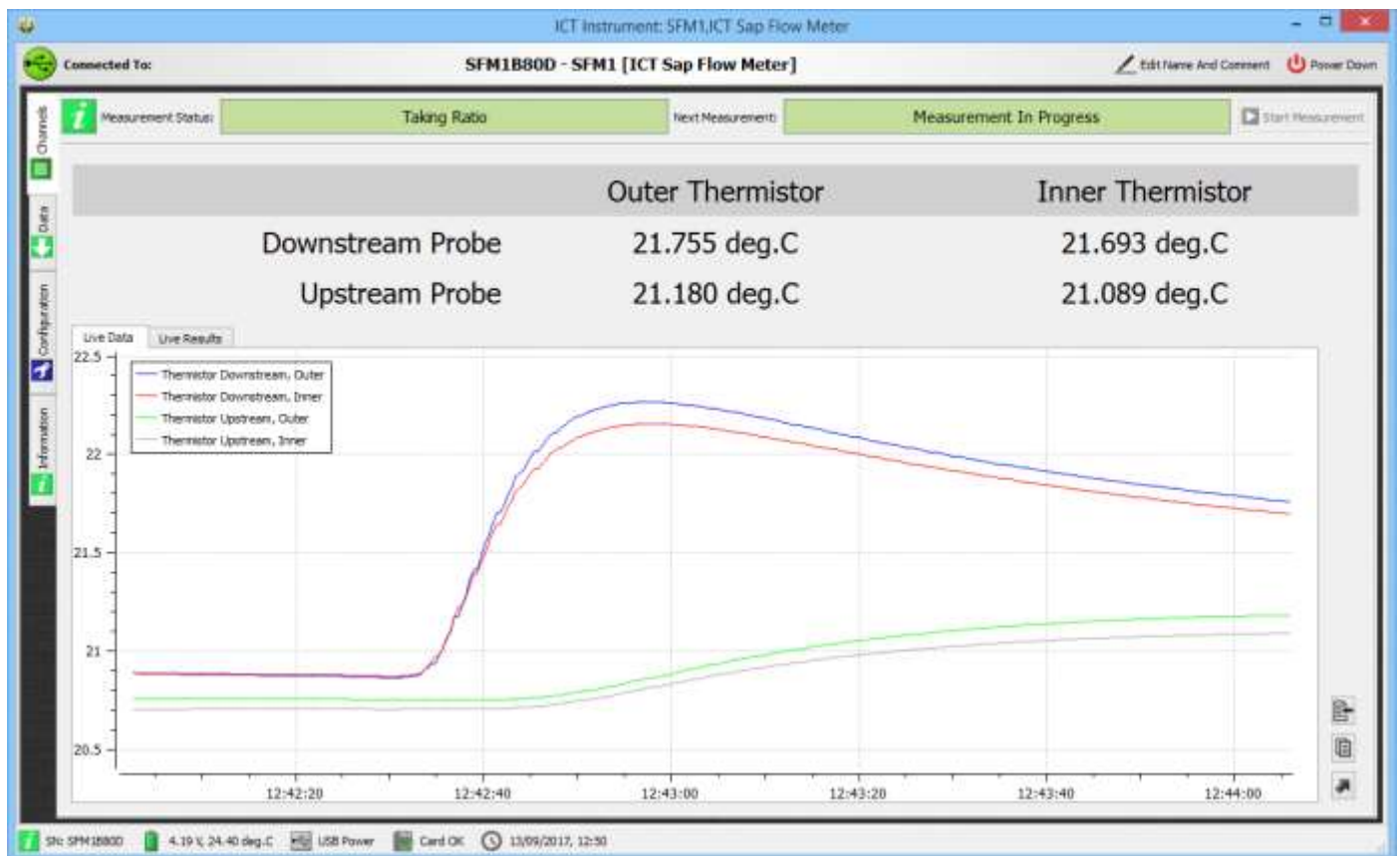
Figure 12: Live measurement results showing the measured heat pulse.

If the temperatures do not rise there may be an issue with the heater. If so, an error code will be reported in the instrument data file (temp rise insufficient). If the instrument is functioning correctly a sap velocity value within the range of 12 to 18 cm hr^{-1} will be displayed in the Live Results. Once fully charged the instrument is ready for field deployment.

If the instrument does not return a sap velocity within this range, please contact ICT international via our web site:
www.ictinternational.com/support/rma-form/ and submit a ticket explaining the issue.

Connected To: **SFM1B80D - SFM1 [ICT Sap Flow Meter]** Edit Name And Comment Power Down

Measurement Status: Measurement Stopped | Next Measurement: Manual Mode | ▶ Start Measurement

	Outer Thermistor	Inner Thermistor
Downstream Probe	--	--
Upstream Probe	--	--

Live Data | Live Results

Time	Heat Pulse Velocity (O)	Heat Pulse Velocity (I)	Sap Velocity (O)	Sap Velocity (I)	Sap Flow kg (O)	Sap Flow kg (I)	Max TdOut	Max TdIn	Max TuOut	Max TuIn	Av Rise (O)	Av
2017/09/13 12:28	15.79	16.26	14.51	14.91	2.99	2.74	21.34	21.22	20.32	20.19	1.03	0.98
2017/09/13 12:37	-20.20	-1.22	-16.59	-0.19	-3.42	-0.04	20.36	20.34	20.40	20.37	0.27	0.30
2017/09/13 12:44	16.86	17.97	15.44	16.39	3.18	3.01	22.26	22.15	21.18	21.09	1.04	0.94

SN: SFM1B80D | 4.19 V, 24.40 deg.C | USB Power | Card OK | 13/09/2017, 12:51

Figure 13: Live measurement results – the second measurement is indicative of insufficient heat pulse.

15.5.1.3 Ten Minute Logging

Ten (10) minutes is the minimum logging interval recommended for long-term automated data collection. Data collected more frequently than this has a high probability of damaging the plant tissue surrounding the heater needle and introducing an error due to heat stored in the stem. From a physiological perspective 10 minutes is an adequate frequency of measurement to capture normal plant response to changes within the ambient environment. Plants typically don't respond faster than this in response to changing light levels or Vapour Pressure Deficits (VPD) (the key drivers of transpiration) as there is a capacitive lag within the plant between the atmospheric demand and the plant's supply of water.

NOTE 29: Where specific targeted artificial stimuli are applied to the plant, in particular, irrigation of a drought affected plant or cutting experiments, a frequency of measurement greater than 10 minutes may be beneficial. For these instances ICT recommends the use of the HFD8 Heat Field Deformation Sap Flow Meter which is a continuously heated technique allowing logging frequencies of every 1 second.

15.5.1.4 60 Minute

This is a good temporal resolution for long term field deployments where only daily water use values are of interest and it is beneficial to minimize the volume of data collected. Logging intervals greater than 60 minutes are not provided as data collected at such an interval begins to filter important physiological responses effectively introducing error to the interpretation of the data.

15.5.2 Reporting Options

The SFM1 Sap Flow Meter provides two Reporting Options:

Needle Temperature Mode or Sap Flow Mode.

15.5.2.1 Sap Flow Mode

Sap Flow Mode is the standard and recommended measurement mode.

The Sap Flow Mode provides automatically processed sap flow results in Raw Heat Pulse Velocity, Corrected and Uncorrected Sap Velocity, and Sap Flow.

Raw Heat Pulse Velocity can be post processed in Sap Flow Tool; however Corrected Sap Velocity and Sap Flow cannot be reprocessed once logged in these units.

Alternatively, post processing can be applied to the Uncorrected measurements using CIS.

In order to use the Corrected Sap Velocity and Sap Flow data automatically logged by the Sap Flow Meter, you must enter the relevant correction parameters into the Corrections tab. This feature is suitable where the SFM is being installed on a tree or species with known parameters.

NOTE 30: Sap Flow Mode is generally recommended as it allows for the easiest data manipulation and post processing. Sap Flow Mode records data in csv format, suitable for use with Excel or CIS.

15.5.2.2 Needle Temperature Mode

Needle Temperature mode is recommended only for detailed scientific research. The raw needle temperatures measured throughout the measurement cycle are recorded at a frequency of 3 Hz, although the user can adjust this between 1 and 30 Hz (see SD Card Logging Options for details). This mode then provides internal stem temperatures at two points radially across the sap wood and the data can be post processed in Sap Flow Tool Software.

The advantage of this feature is that correction parameters can be collected subsequent to installation (rather than prior to) and that data can be reprocessed at any time instantly should any correction parameter be revised. Additionally, Sap Flow Tool provides the ability to analyse the raw heat pulse data with a range of sap flow algorithms (HRM, HRMx, CHPM or TMax).

WARNING 7 - Needle temperature mode does not record data in the normal csv format. Data recorded in needle temperature mode requires processing with Sap Flow Tool software.

NOTE 31: To operate the SFM1 Sap Flow Meter in CHPM mode, the needle spacing must be adjusted from symmetrical spacing 5 mm either side of the heater to asymmetrical spacing 5 upstream and 10 mm downstream of the heater.

15.5.3 Measurement Suspend and Time Delay

Time delay/Delayed Start allows you to set the time when measurements will start, based on their scheduled interval. Measurements will not take place prior to this time.

Measurement can be delayed up to 23 hours, 59 minutes and 59 seconds.
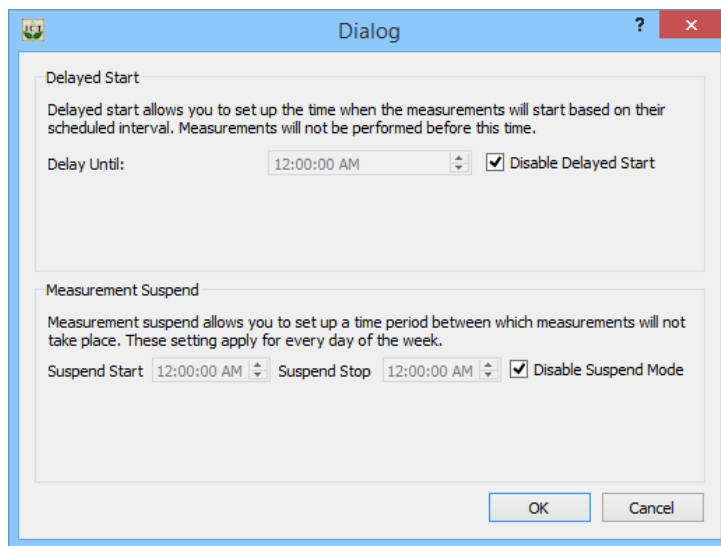
Figure 14: Delayed Start and Measurement Suspend options.

Delayed Start is particularly useful for setting up a number of SFMs to begin logging at the same time prior to their installation in the field. If a longer delay time is desired (days, weeks), turn off the instrument for the intervening period and switch it on again on the day of operation.

For example, if on Friday morning the instruments are configured to "Delay Until: 17:00" and then turned off until Monday when installation is planned, the instruments can be installed and turned on but they will not commence logging until 17:00 (5:00pm) that day. This will mean all instrument data sets will commence at the same time and no laptop is required in the field to set the Sap Flow Meters logging.

NOTE 32: For greatest accuracy, synchronise the real-time clocks of all SFM units to your computer's time prior to installation in the field. This can be done by clicking the date and time at the bottom of CIS.

Measurement Suspend allows you to set up a period of time in which measurements will not be taken. This is typically used to save power by not taking measurements when the plant is not transpiring.
Measurement Suspend is not generally used or recommended.

15.5.4 Pulse Energy

The factory default Heat Pulse Energy setting is 20 Joules. All SFM1 Sap Flow Meters are configured to this energy level to prevent inadvertent damage to the plant caused by installing the instruments and having the energy level set too high for the species or prevailing ambient environmental conditions.
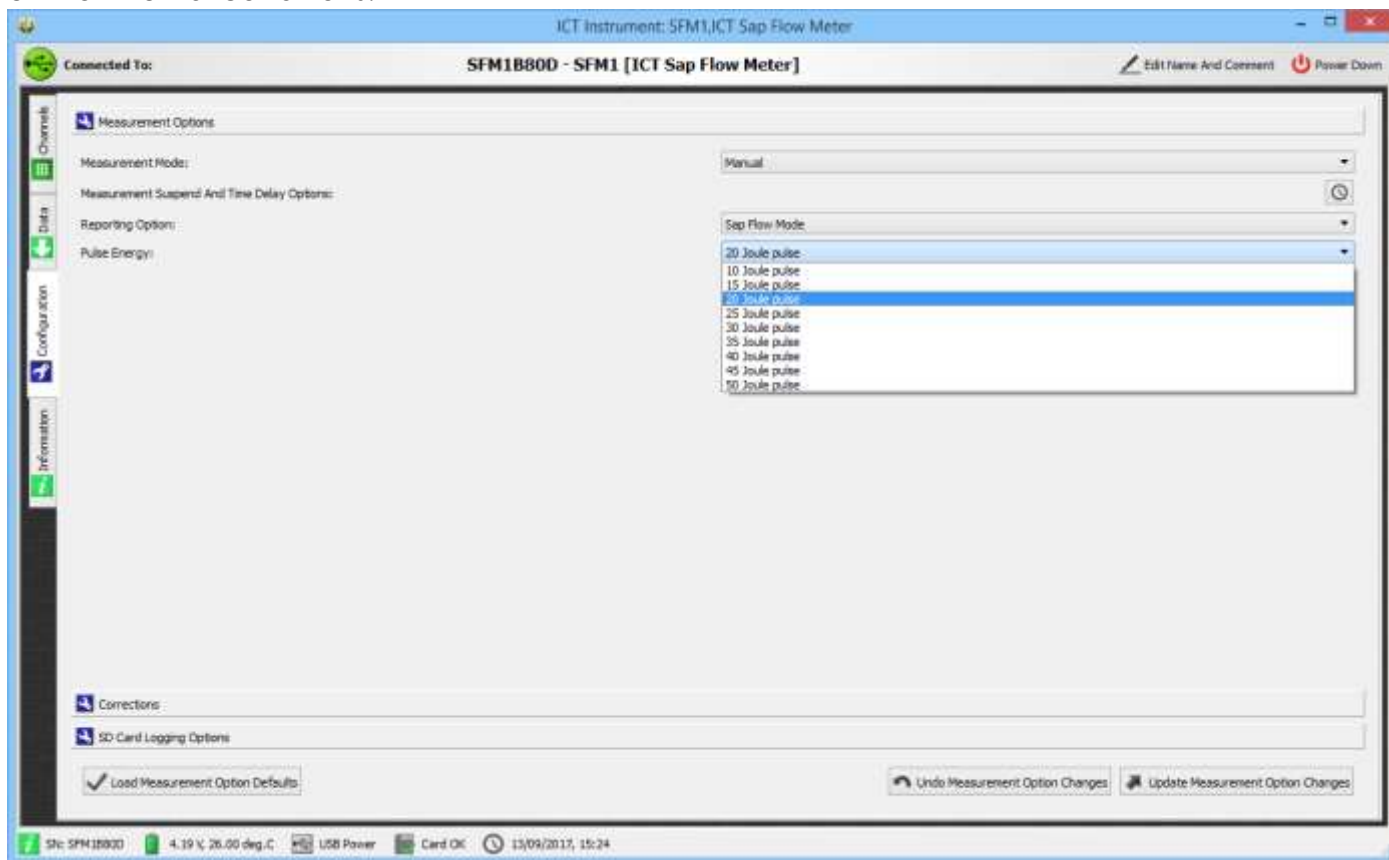
Figure 15: The Pulse Energy setting can be changed from the default value of 20 Joules using the dropdown menu. Click Update Measurement Option Changes to store the settings on the SFM.

As the HRM principle is based on the ratio of temperature rise, the absolute temperatures are not important. The key factor to consider when setting the Heat Pulse Energy is that a minimum amount of heat is used in order to register a temperature rise and provide an accurate reading. Too much heat will not improve the accuracy of the measurement and can have a serious damaging impact on the plant tissue immediately surrounding the needles, which will impact the accuracy of the reading by masking or reducing the movement of heat from the needle to the water conducting xylem, effectively thermally decoupling the needle from the sapwood it is intended to measure.

For these reasons, maximum temperature rise should be kept between 0.7 and 1.5°C.

NOTE 33: If the temperature rise is less than 0.7°C increase the energy level until the temperature rise is within 0.7°C to 1.5°C. This range ensures good results and will help to eliminate measurement errors. This is especially important during periods of high flow where a lower amount of energy (20 Joules) may be insufficient to generate a measurable temperature rise at the upstream measurement location due to rapid convection of heat away from the thermistor.

An energy level of 20 Joules is a safe level for most applications, however it may be necessary to increase this level in species with high sap flow rates or under conditions of extreme transpiration. Determining the correct conditions to increase this level is best done empirically by logging and reviewing the maximum temperature rise logged as a parameter in the data file of the SFM1. If the SFM1 determines that the maximum temperature rise is less than the acceptable threshold, a diagnostic comment, such as "temperature rise insufficient", will be recorded in the data file. This message indicates that a higher Pulse Energy level should be applied. In small sensitive plants, an energy level of 10 Joules may be required to prevent damage to the plant.

NOTE 34: Tree size does not affect the Pulse Energy requirements as long as the needles are fully inserted, however wood moisture content and density can.

15.5.5 Corrections

Correction parameters are applied to the measurements in real time, displayed in the data file as 'Corrected' parameters. These options can prove to be convenient in some situations, however ICT recommends that data processing be performed in CIS, Excel or Sap Flow Tool.
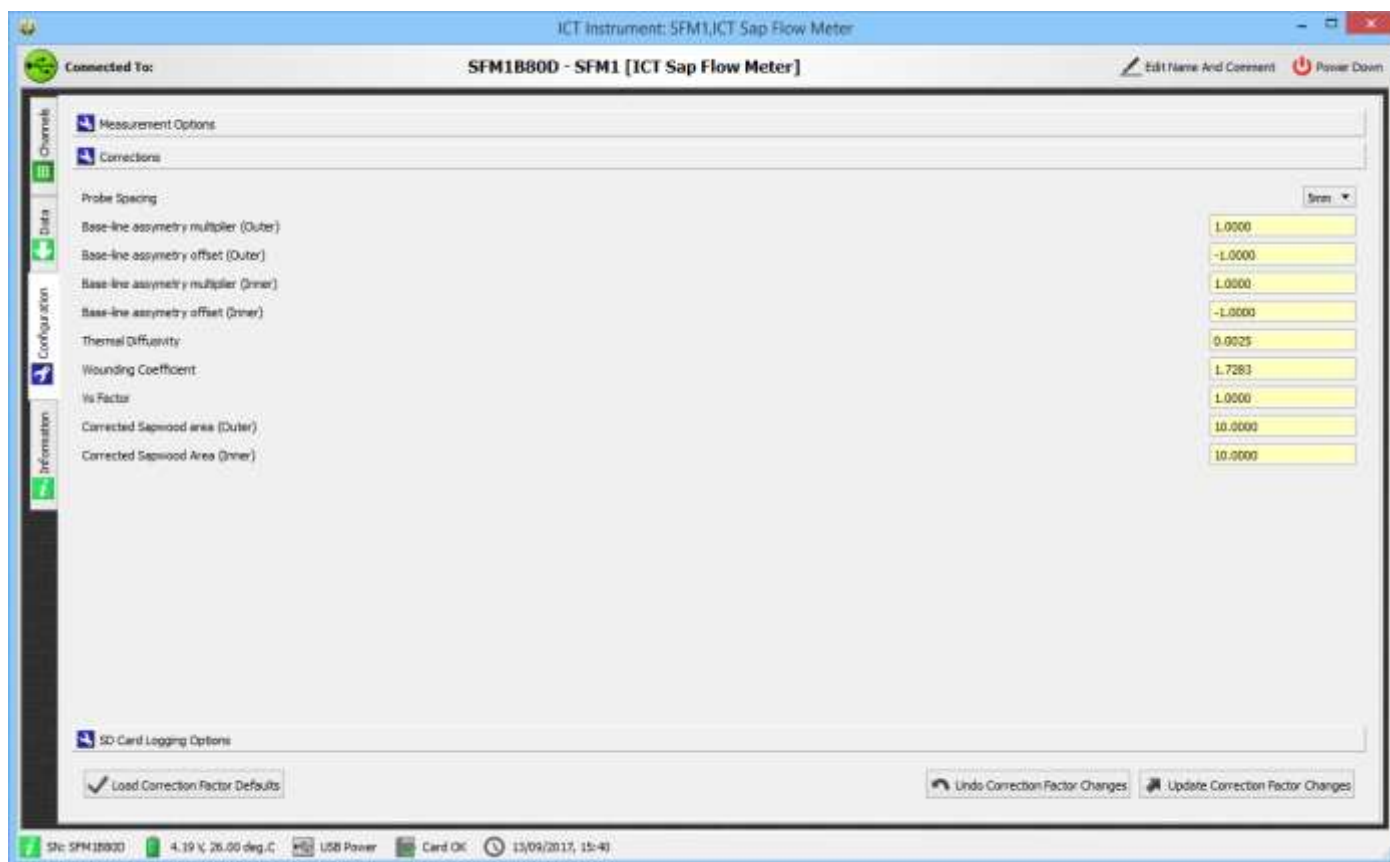
NOTE 35: The default Correction parameters are likely incorrect for any scientific presentation of data. It is important to use the correct values for the plant being measured or to post process the data.

15.5.5.1 Probe Spacing

Probe (or needle) spacing is an important parameter as heat pulse velocity and sap velocity is dependent on an exact distance between probes.

$$V_h = \frac{k}{x}\ln\left(\frac{v_1}{v_2}\right) x 3600 \text{ cm h}^{-1} \qquad\qquad \text{Equation 9}$$

Where:
k is the thermal diffusivity of wet wood.
x is the distance between the heat source (heater) and temperature sensors.
v_1 and v_2 are the increases in temperature (from ambient) at equidistant points downstream and upstream from the heater.

The original HRM principle was developed using spacings of 6mm between probes. Subsequent refinement of the principle demonstrated that 5 mm spacings increased the maximum measurable flow rate from 45 cm hr^{-1} to 54 cm hr^{-1}. It was hypothesised that further increases to the maximum measurable flow rate for species with wide xylem vessels (e.g. vines) could be achieved by reducing the distance between needles to 4 mm. This hypothesis was never tested.

The factory default setting is 5 mm and ICT International recommends that all installations utilise the 5 mm needle spacing only. This 5 mm spacing is suitable for all flow rates from -20 cm hr^{-1} to a theoretical maximum (proposed in the 1950s by Marshall) of 54 cm hr^{-1}. Empirical tests have

proven the high precision and high accuracy dedicated electronics of the SFM1 Sap Flow Meter can measure velocities of 100 cm hr^{-1} in artificial environments where a high-pressure pump was used to force water through a cut stem segment at a range of velocities from 0-100 cm hr^{-1}.

Increasing the spacing between the needles to 7.5 or even 10 mm can exponentially reduce the error caused by misalignment or divergence of the needles from parallel. This is because the percentage error of the distance between needles is less when spaced wider apart.

NOTE 36: The 6 mm spacing is still relevant and can be used, making a legacy provision for scientists who may already have existing data collected at 6 mm spacings and wish to maintain uniformity of their data.

15.5.5.2 Probe Symmetry

Probe spacing and precise parallel alignment are the most significant sources of error in all heat pulse velocity techniques. A small 0.5mm misalignment of either SFM1 needle can affect the accuracy of measurement by +/- 4%. A large 3mm misalignment of the needle during installation results in a 22% error of heat pulse velocity.
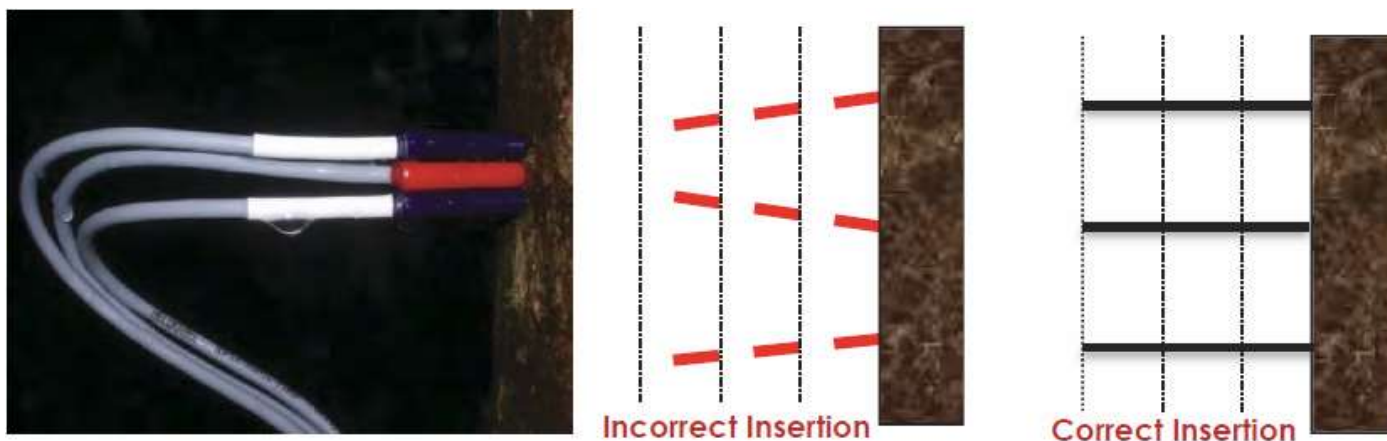
Photo 15: SFM1 probe alignment and the importance of symmetrical installation.
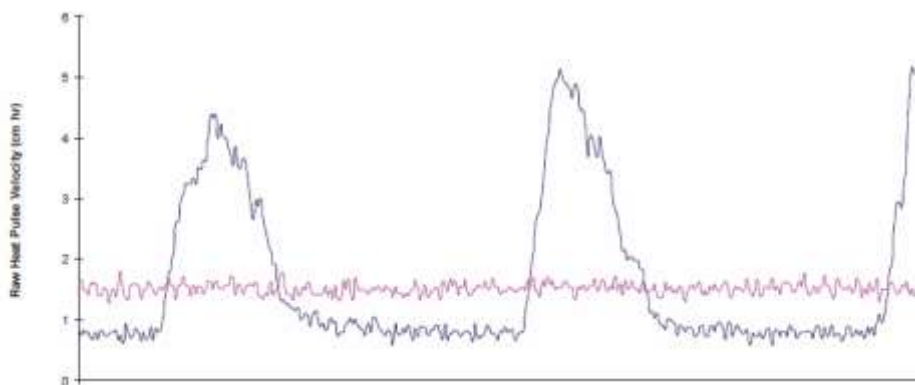
Figure 17: Positive zero offset with inner measurement point (pink) located in heartwood.
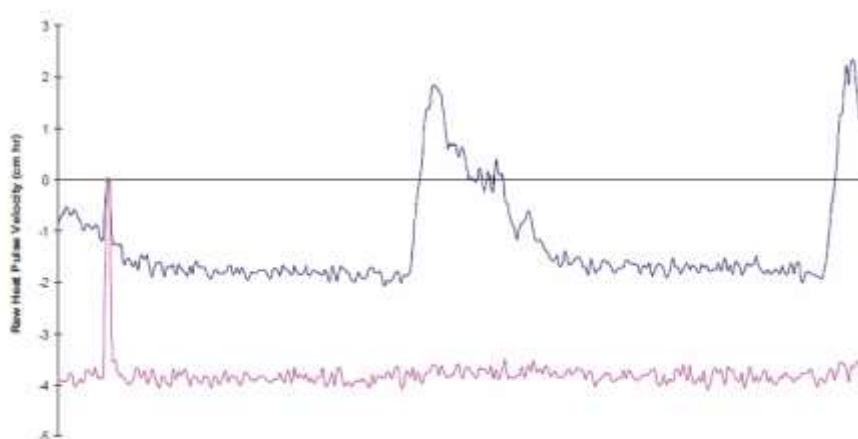
Figure 18: Negative zero offset with inner measurement point (pink) located in heartwood.

Corrections for small needle misalignments are made using a multiplier and offset derived from a simple linear relationship between corrected and uncorrected sample data. Large errors in needle misalignment cannot be corrected and the installation should be abandoned and the instrument reinstalled.

As the exact identity of which needle is incorrectly spaced cannot be obtained by data analysis, an intermediate solution that assumes both temperature needles contribute to the error is used. This creates least bias in the data correction and once performed allows accurate discrimination of positive and negative sap flows. Corrections can be manually derived by solving equations 3 and 4 (Correction for Probe Misalignment) as outlined in the extract from Burgess et.al 2001 in the section Heat Ratio Method Theory. Alternatively, Sap Flow Tool Software provides a linear transformation function that semi-automates the process of correcting for probe misalignment or asymmetry of installation.

Base-line Asymmetry Multiplier (BLAM)

Fields to enter BLAM for both Outer and Inner measurement points are supplied. Values must be between +2 and -2, with an accuracy of 4 decimal places. Typical values for BLAM range from 1, where no misalignment exists, up to 1.385 for base-line asymmetry of ±5.62cm h^{-1} for misalignments of ~3mm from parallel.

The default value is 1, as this does not affect the measurements.

Base-line Asymmetry Offsets (BLAO)

BLAO for both the outer and inner measurement points. The range is between +5 and -5, with an accuracy of 2 decimal places. If BLAO is above ±5, Sap Flow Tool can be used for post processing up to ±7.78.

NOTE 37: Whether the offset is a positive or negative adjustment will depend upon the convergence or divergence of each needle relative to the heater. The magnitude of the adjustment can only be assessed after an initial few days of measurements have been analysed. Therefore, this correction parameter must be entered after the first few days of data have been collected.

15.5.5.3 Thermal Diffusivity

The thermal diffusivity (k) of the green (fresh) sapwood explains the complex relationship between diffusion of heat through a woody matrix of water and parallel, straight lignified tubes (vessels or tracheids) that make up the sapwood. A nominal thermal diffusivity value of 0.0025 cm² s⁻¹ is initially assigned for calculating heat pulse velocity (V_h) and further resolved once sapwood properties are measured to calculate corrected sap velocity (V_s). The corrected thermal diffusivity (k) of the specific sample will lie between a range of 0.001 (pure water) and 0.004 (dry wood).

The thermal diffusivity (k) is empirically calculated in cm² s⁻¹ from Equation 10 (Marshall 1958):

$$k = \frac{k_{gw}}{pc} 10000 \qquad\qquad \text{Equation 10}$$

Where: K_{gw} is thermal conductivity, p is density (kg m³) and c is specific heat capacity of green (fresh) wood.

The value of K_{gw} was first calculated according to Equation 11 modified from Swanson (1983):

$$K_{gw} = K_s\, m_c \frac{p_b}{p_s} + K_w(1 - m_c \frac{p_b}{p_s}) \qquad\qquad \text{Equation 11}$$

Where: K_s is thermal conductivity of water (5.984 x10⁻¹ J m⁻¹ s⁻¹ °C⁻¹ at 20°C (Lide 1992)), m_c is water content of sapwood, p_b is the basic density of wood (dry weight/green volume), ρ_s is the density of water and K_w is thermal conductivity of dry wood matrix. We calculated K_w as Equation 12 (Swanson 1983):

$$K_w = 0.04182(21.0 - 20.0\, F_v) \qquad\qquad \text{Equation 12}$$

Where: F_v is the void fraction of wood defined as (cf. Swanson 1983):

$$F_v = 1 - \left(\frac{p_b 0.6536 + m_c}{1000}\right) \qquad\qquad \text{Equation 13}$$

Specific heat capacity of green wood was calculated according to its constituent parts (modified from Edwards and Warwick 1984):

$$c = \left(\frac{w_d c_w + c_s(w_f - w_d)}{w_f}\right) \qquad\qquad \text{Equation 14}$$

Where: w_f is fresh weight and w_d is oven-dried weight of the sample (kg). Water content and density of the sapwood are measured on wood cores taken at the time on installation.

See Chapter 24 for the fresh weight and dry weight measurement process.

NOTE 38: If entering the correction factors directly to the SFM1 for real-time processing, Thermal Diffusivity should be sampled and determined prior to installation. The process can take up to a week due to the drying time of sap wood.

15.5.5.4 Wounding Coefficient

Installing the SFM needles causes mechanical damage and interrupts flow by occlusion of the xylem conduits. This results in an area of non-conducting tissue directly surrounding the needle. Correction for this response is important to achieve accurate results. Wound correction coefficients applicable to a range of wound sizes have been generated using numerical models which allow accurate corrections to be made. If the wound size or a characteristic wound size for the sample species is known, the corresponding wound correction coefficient can be entered into the SFM1 at the time of installation & set up.

Alternatively, if the wound correction for the sample species is not yet known, or a more accurate direct measurement of wound size from each specific instrument installation is preferred, a destructive sample must be taken of the sample tree after the experiment. This data can then be used to determine the wounding coefficient from Table 1 below (use linear approximation B). These corrections are automatically applied to the Raw Needle Temperature or Raw Heat Pulse Velocity data in the Sap Flow Tool software when a wound diameter is selected.

Photo 16: Wound response around the needles after uninstallation. The dark area surrounding the central heater needle hole is more pronounced due to the heat input to the water conducting tissue.

NOTE 39: Due to varying wound response and slight asymmetries caused by the installation procedures, heat ratios vary over time. For this reason, readings are sampled multiple times between 60 seconds and 100 seconds after the heat pulse. This is when the heat ratios are most stable and linear.

Photo 17: Manual measurement of the wound size of a destructively sampled cross section, cut through one of the needle positions.

B. -0.5, 0, 0.5-cm probe configuration

Wound (cm)	b	c	d	r^2	B	r^2
0.17	1.6821	-0.0015	0.0002	1.0000	1.7283	0.9993
0.18	1.7304	-0.0013	0.0002	1.0000	1.7853	0.9992
0.19	1.7961	-0.0016	0.0002	1.0000	1.8568	0.9991
0.20	1.8558	-0.0018	0.0003	1.0000	1.9216	0.9990
0.21	1.9181	-0.0021	0.0003	1.0000	1.9891	0.9989
0.22	1.9831	-0.0024	0.0004	1.0000	2.0594	0.9988
0.23	2.0509	-0.0028	0.0004	1.0000	2.1326	0.9987
0.24	2.0973	-0.0030	0.0005	1.0000	2.1825	0.9987
0.26	2.2231	-0.0037	0.0006	1.0000	2.3176	0.9985
0.28	2.3760	-0.0046	0.0008	1.0000	2.4813	0.9983
0.30	2.5232	-0.0055	0.0010	1.0000	2.6383	0.9982

Table 1: Correction coefficients for numerical solutions derived for a range of wound diameters and corresponding to a –0.5, 0, 0.5 cm probe configuration, with 1.3 mm diameter stainless steel probes. Solutions were derived based on modelled temperature data at t = 60–100s. Coefficients b, c and d apply to Equation 6. Coefficient B is a linear approximation (Equation 16) of the polynomial relationship described by Equation 6. (A full table including coefficients for previously recommended -0.6, 0, 0.6 cm probe spacing is included in Appendix 23.1)

15.5.5.5 Vs Factor

The factor is a multiplier used to convert corrected Heat Pulse Velocity (V_c) to Corrected Sap Velocity (V_s) as outlined by the relationship developed by Marshall 1958 (Equation 7) The range spans 0.5 to 1.5 with a resolution of 2 decimal places.

15.5.5.6 Sap Wood Area

Sap Flow (mass solute transport), or water movement within a tree stem, branch, or root can be expressed as a volumetric measurement by multiplying the corrected sap velocity (V_s) by the cross-sectional area of conducting sapwood. The sapwood area is calculated by the cross-sectional area under-bark after discounting the heartwood area.

When calculating sap flow in gm hr^{-1} (the equivalent of cm^3 hr^{-1} or ml hr^{-1}) the two radial measurement points of the SFM1 needle are integrated, using a weighted average. The weighting is calculated by determining the sapwood area for each annulus. Where the annulus division is made halfway between the two measurement points and the sapwood area calculated for each by knowing the depth of bark, heartwood boundary and stem diameter.

The sapwood area is typically determined during installation by taking a sapwood core with a coring tool. A dye is then applied to the core which stains the heartwood a darker colour than that of the sapwood. The typically clear differentiation between the two tissues based on pH content enables a direct measurement of radial thickness of the sapwood or water conducting xylem. The Cross-Sectional Area can then be calculated. Each of the two annulus measured by the Inner and Outer Measurement points are then multiplied by the corresponding area.
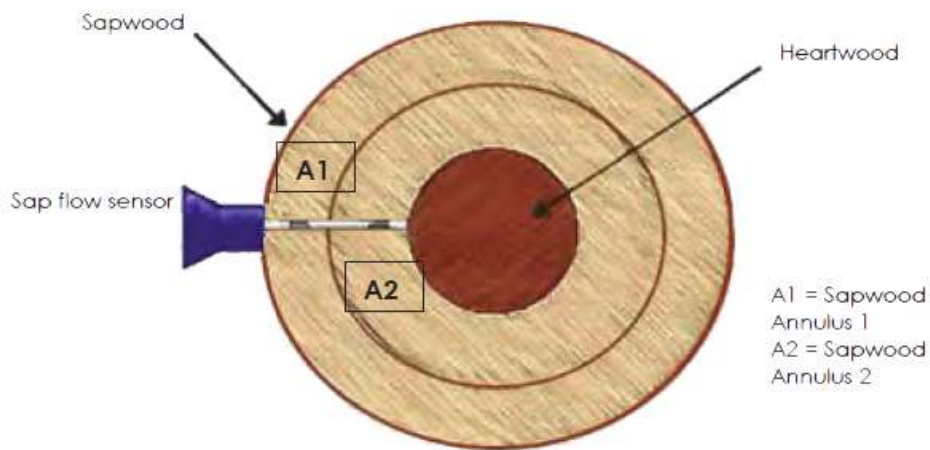
Figure 19: Accounting for radial sap flow gradients when calculating volumetric sap flow.

The weighting is calculated by:

Corrected sap velocity (10 cm hr^{-1}) x sapwood area (220 cm^2) = 2,200 cm^3 hr^{-1} for annulus 1

+

Corrected sap velocity (5 cm hr^{-1}) x sapwood area (40 cm^2) = 200 cm^3 hr^{-1} for annulus 2

This results in a single sap flow value for the whole tree of 2,400 cm^3 hr^{-1} or 2.40 litres hr^{-1}.

These calculations are automatically performed provided the values for sapwood area for both the outer and inner measurement points have been entered.

The valid entry range is between 10.0000 cm^2 to 99,000.0000 cm^2, to 4 decimal places.

A typical example sapwood range is between 12.37 cm^2 for very small diameter trees to 1600.00 cm^2 for very large diameter trees.

15.5.6 SD Card Logging Options

15.5.6.1 Probe Selection

Inner Only, Outer Only or Inner and Outer. Inner and Outer is the default option, and will record both measurement points.
Inner Only and Outer Only are intended to be used in small stems where both measurement points are not within the plant.

15.5.6.2 Calculated Results

Available parameters are:
Raw Heat Pulse Velocity
Sap Velocity
Sap Flow in kg

All of these are logged by default.

15.5.6.3 Diagnostic Temperature Data

Diagnostic Temperature Data records the max temperature, average temperature rise, and temperature ratios during the heat pulse measurement. This is not enabled by default, but can be useful when troubleshooting measurement problems.

15.5.6.4 Power Management

Available parameters:
Internal Battery
External Supply

These record the status of the internal battery and external power supply. Both are enabled by default, and ICT International strongly recommend logging Internal Battery and External Supply, as this is useful for troubleshooting and diagnostic purposes.

16   Install the Sap Flow Meter

Care must be taken to install the sensor. Ensuring the needles are parallel and aligned axially is imperative to collecting good data. Corrections can be made but there is no substitute for good preparation and installation of the needles. It is recommended that you watch the installation video before beginning the installation for the first time.

16.1   Selecting a Measurement Tree

Select a measurement tree or plant that is representative of the environment in which you are sampling. Your experimental hypothesis will provide the necessary guidelines to determine this. Additional considerations that should be considered, providing they do not conflict with your experimental goals, are:

1. Select a tree that is not obviously dead or dying and has not sustained abnormal physiological trauma such as physical damage, fire, insect damage or poisoning.
2. Consider partitioning the sample trees by sap wood area based on a de-facto parameter of stem Diameter at Breast Height Over Bark (DBHOB). Break the trees into size classes and measure sub samples of trees within these size classes.
3. Avoid the impact of "edge effect" by not measuring trees on the edge of a forest or clearing where ambient environmental conditions may be significantly different to those experienced by the majority of the other trees in the experiment.

16.2   Measure the Stem Diameter

After selecting the trees that satisfy the limits of the experimental protocol, begin by measuring the stem diameter of each tree. Measure all trees at the same point for comparison. The convention used in forestry is to measure at 1.3m above the ground over the bark, this is known as Diameter at Breast Height Over Bark (DBHOB) as this provides a well-known reference for comparison between experiments.

Use an inextensible steel or fiberglass diameter tape that is graduated in centimetres (cm) and calibrated on both sides; one in diameter and the other circumference.

16.2.1 How to convert stem Circumference to stem Diameter

If you do not have a dual calibrated diameter tape it is possible to simply measure stem circumference with a conventional tape and convert the measurement to stem diameter. Using the equation for the Diameter of a Circle:

$$d = C/\pi$$ Equation 15

Where:
d = diameter
C = Circumference of the Circle
π = Pi (3.142)

16.2.2 Stem Diameter Measuring protocol

(1) First determine where breast height (1.3m) is on your body and use this as the guide for the height at which all measurements will be made on the sample trees.

(2) On uneven or sloping ground always stand on the upslope or high side of the tree as the reference point for making the measurement at DBHOB.

(3) Remove any old, rough, loose bark that is clearly senesced. The reference point should be as close to new living tissues as possible to ensure an accurate and stable measurement. Poor sampling technique that fails to ensure this can result in erroneous data due to a net contraction in DHBOB between seasonal measurements that masks the true physiological growth.

(4) Select a location on the stem that is devoid of any obvious swellings, distortions or branches. If necessary move the tape above and below the obstruction by up to 10 cm and take an average reading.

(5) Wrap the tape around the tree, at right angles to the main stem. Be careful not to twist the tape then pull the tape tight on either end. Be sure never to cross your arms to record the measurement as this will obscure the tape and or skew the measurement.

(6) Read the measurement to a resolution of 1 decimal place.

Photo 18: Measuring stem Diameter at Breast Height Over Bark (DBHOB) using a diameter tape.

16.3 Measure Bark Depth

Begin by removing any loose flaky or rough fibrous bark to achieve a reference point from which to measure. This should already have been done prior to measuring the stem diameter.

NOTE 40: The SFM1 should be installed at the same point at which the stem diameter and bark depth are measured.

16.3.1 Bark Depth Gauge

Measure the bark depth using a bark depth gauge. This is a dedicated tool that consists of a sharp curved blade that slides inside a calibrated scale graduated in mm. The handle of the blade provides a large base upon which to push the blade into the stem. The sharp blade is specifically curved so that it cuts through the soft outer bark fibres but cannot penetrate the denser xylem fibres of the sap wood. If it was not curved the blade could continue to be forced under pressure into the xylem fibres, splitting them apart and resulting in an erroneous measurement of bark depth that makes it appear deeper than it actually is.

Photo 19: Bark Depth Gauge (left) and using a Bark Depth Gauge to determine bark thickness (right).

16.3.1.1 Using a Bark Depth Gauge

Place the end of the bark depth scale against the stem of the tree then firmly push on the handle of the tool forcing the blade through the bark. The blade will cut through quite easily until it strikes the sapwood. At this point the user will feel a difference in the resistance and will not be able to push the blade any further. It may also be possible to hear the blade striking the xylem.

16.3.1.2 Using a Flat Blade Screwdriver for Bark Depth

A flat blade screwdriver can be used turned in the horizontal plane. Using a hammer, hammer the screw driver into the stem until it stops moving. You should hear a change in the pitch of the noise of hammering the screw driver that coincides with an abrupt change in resistance as the blade strikes the sap wood. This indicates the sap wood has been reached. Mark the edge of the tree on the screw driver, remove and measure this distance, this is the bark thickness.

Using a flat blade screwdriver in the vertical orientation will split the fibres and will not provide a measure of the bark depth.

16.4 Measure Sapwood thickness

A coring tool can be used to determine the sapwood depth/thickness. Bore the coring tool into the stem at least half way through the tree to ensure that the core passes through the sapwood into heartwood. Remove the sapwood core and stain with an indicator dye. Measure the sapwood thickness. Knowledge of the sapwood thickness can be used to ensure that the measurement points of the SFM1 needles can be correctly positioned within the water conducting xylem of the tree.

Photo 20: Stem cross sections of two different tree species, *Eucalyptus sideroxylon* (left) and *Callitris glaucophylla* (right) illustrating the variability of sap wood and bark thickness. This variability between species highlights the importance of knowing the thickness of both bark and sapwood so that the radial measurement points of the SFM1 needles can be positioned in water conducting tissues.

16.4.1 Extracting a Sapwood Core

At the start, and until the corer engages into the tree a few millimetres, push only moderately hard. Do not use excessive force or attempt to hammer the corer into the tree, as this may break the corer.

The core should be initialised by pushing the corer into the tree and turning it at the same time. This will help maintain a proper corer alignment and provide a stable pivot point for the core barrel to prevent corkscrewing.

Photo 21: Gently guiding the coring tool at the start of a sap wood core.

After the coring tool has penetrated the sap wood use two hands to apply more force, but continue to maintain a level and perpendicular orientation to the tree. Continue boring into the stem until the centre of the tree has been reached. This will ensure the full thickness of the sap wood has been sampled.

Once the centre of the tree has been reached, the coring tool will have cut a thin continuous core of wood crossing the bark, sapwood and heartwood interfaces. Insert the extractor sleeve and twist the handle in the opposite direction to break the core attachment to the tree. Keep the extractor sleeve pushed firmly into the handle of the coring tool throughout this process. This is very important to ensure the core stays intact. Slowly remove the extractor sleeve together with (hopefully) the intact core sample.

Photo 22: Withdrawing the intact sapwood core using the extractor sleeve.

Photo 23: Applying Methyl Orange indicator dye.

WARNING 8 - The increment borer should be removed from the tree immediately after the core has been extracted or it may become stuck.

When the core is removed, apply an indicator dye to the sample, such as Methyl Orange ($C_{14}H_{14}N_3NaO_3S$, provided by ICT with the coring tool). The indicator dye will stain and differentiate the sapwood from the heartwood. Allow sufficient time for the indicator dye to absorb into the fibres before measuring.

After approximately 15 minutes (response time varies considerably between species) a distinct colour change becomes evident between the actively conducting xylem of the sapwood and the non-conducting xylem of the heartwood. The lighter coloured area is the sapwood and the dark region is the heartwood. The heartwood stains darker due to the build-up of tannins associated with the lignification process of heartwood.
Use a rule or callipers to precisely measure the radial depth/thickness of the sapwood.

Depending upon the pH of the sapwood different dyes may be required. As an example, Methyl Orange works well with many Eucalyptus species as it turns the sap wood yellow and the heart wood a deep red colour.

If additional Methyl Orange is required, it can be purchased from Laboratory and Chemical supply companies in powdered form.

16.4.1.1 Mixing instructions for Methyl Orange Indicator
Methyl Orange is very potent, only requiring a small number of granules to make sufficient volume of solution. The standard mixing concentration is a 0.1% solution.
In a glass beaker measure out 0.1 gm per 100 ml of deionized distilled water. Best results are obtained when dissolving Methyl Orange in hot, deionized distilled water. Stir the granules until they fully dissolve. Allow the solution to cool, but prior to reaching room temperature decant into an air tight sealed container. Shake the solution vigorously for a several minutes to ensure all granules are dissolved into solution with no precipitate. Finally, decant into a 15 ml eye dropper bottle for use in the field as required. Store the remainder of the solution in the air tight storage container.

WARNING 9 - Be sure to take appropriate care following safety guidelines both of the Methyl Orange MSDS and when using hot water.

16.4.2 Destructive Sampling to Measure Sapwood

In some plant tissues it's not always possible to obtain a definitive sap wood thickness because the colour differentiation between heartwood and xylem is indistinct even when using a pH indicator. An alternative option is to perform destructive sampling. This has obvious disadvantages in that it signals the end of the experiment to measure sap flow in the tree. Nevertheless, if performed at the end of the experiment it can provide a definitive verification of the sap wood thickness using more precise methods. The first is obviously a direct empirical measure of the transverse section of the stem segment using a rule. However, this may not yield definitive answers.

Photo 24: A destructive empirical measure of a transverse stem section using a ruler to determine the sapwood thickness. Species such as *Calitrus glaucaphylla* have a distinct delineation between sapwood (white tissue) and heartwood (reddish brown tissue towards the centre of the stem). Other species may require microscope evaluation of the vascular tissue.

16.4.3 Microscopic analysis

Ultimately, where macro visual analysis is unable to differentiate active and inactive xylem, microscopic analysis of transverse thin sections will be able to definitively determine if xylem vessels and or tracheids are open, conducting water, or fully lignified, closed off and not conducting water.
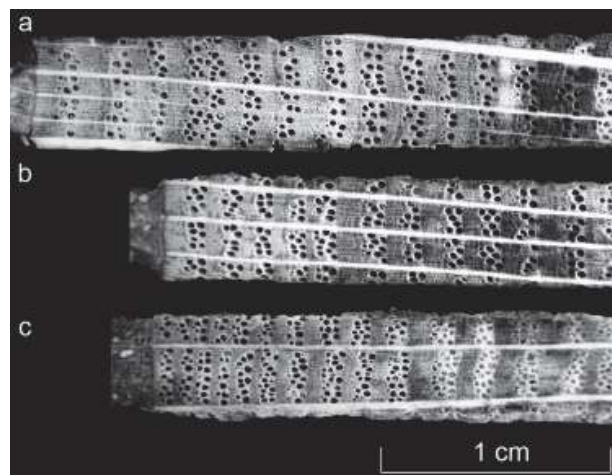
Photo 25: Microscopic analysis of a sapwood transverse section showing the open vessels which confirm the sample to be sapwood.

16.5 Attach the Installation Guide

Select the site on the stem to be measured. It should be a flat, straight section of stem large enough to fit the drill guide with no branches, knots, nodes or obvious insect or pest damage present. Before installing the drill guide, calculate the position within the sapwood of each measurement point. The ideal position of the Outer measurement point is approx. 2.5 mm below the cambium-sapwood interface. This is to ensure the region of highest sap flow, the outer youngest layers of sapwood, are measured.

If the measured bark thickness is greater than 10 mm, the Outer measurement point, 12.5 mm from the base of the needle, will not be located in sapwood and this will result in erroneous, difficult to interpret data. In this situation, it will be necessary to remove sufficient bark to ensure the Outer measurement point is located correctly within the outer sapwood.

NOTE 41: If it is necessary to remove bark, ensure that a sufficient area is removed to accommodate the drill guide so that it can be placed firmly and squarely to the stem, otherwise it will be difficult to drill the holes parallel.

Attach the installation guide to the tree using the 4 anchor pins. For small stems between 10 mm and 25 mm diameter it may be necessary to pack the back of the installation guide with a stick to ensure a stable mounting of the guide on the stem. This should then be held in place with clear adhesive/sticky tape so the holes of the guide are easily visible and can easily be drilled through.

Photo 26: SFM Drill guide attached to a smooth barked *Eucalyptus camaldulensis* (left) and installed on a small diameter branch using sticky tape to secure it in place.

WARNING 10 – The SFM drill guide anchor pins are sharp, take care when removing the drill guide from the tree.

16.6 Drilling

Begin drilling the three holes, beginning from the top position of the drill guide and moving to the bottom hole. The operator should be positioned in a comfortable manner that ensures complete control of the process. Wherever possible, perform the drilling process at chest height. Avoid holding the drill well above or below chest height. Stand to one side, perpendicular to the drill. This allows the operator to maintain the level of the drill. Be sure to complete drilling each hole before moving to the next one.

Do not attempt to drill each hole in a single pass. Only drill short increments of 1-2mm depth on each pass. Within only 1-2 mm depth of drilling the flutes of the drill will fill with xylem fibres and require cleaning. Choosing to continue to drill with the flutes full of fibres will burn the hole.

Photo 27: A comfortable drilling stance will enable the operator to control and maintain the level of the drill.

If you attempt to push the drill into the stem, you may break the drill bit. The drill should be set to the highest speed so that a clean cut is achieved.

It's better to drill a hole too deep rather than too shallow as additional depth has no effect on the measurement and trying to redrill a hole without the drill guide might produce a hole that is not parallel.

16.6.1 Drill bit specifications

The drill bits are 1.3mm diameter x 75mm long. The specifications of these drill bits were chosen to exactly match the diameter of the SFM1 measurement needles. They provide a snug, but not excessively tight fit. The tolerances of both the drill bit and the measurement needle are high, but the fit should not be considered an interference fit. The needles should still be able to be removed without using excessive force. This very close matching of diameters ensures the measurement needles are coupled thermally with the stem resulting in a good, even heat transfer between the measurement needles and the xylem. The length of the drill bit is designed to provide sufficient length to be secured in the chuck of the power drill so that a 35 mm hole can be drilled into the stem with the drilling guide left in place.

NOTE 42: The drill bits used are made of high speed steel to improve cutting performance and longevity. SFM1-55 drill bits are non-standard specifications, replacement drill bits are readily available from ICT International.

16.6.2 Cordless Power Drill

Use a high speed (high RPM) cordless power drill so that you get a good clean cutting action.

NOTE 43: A Dremel cordless power drill is recommended as it has a long-life Lithium Ion battery for long field use and does not have a large, heavy battery located in the handle at right angles to the drill, making it easier to drill parallel holes.

Insert 25 mm or less of the drill bit into the chuck of the cordless drill. Use the length of a sensor needle (35 mm) and thickness of the drill guide (10 mm) to gauge the correct depth of insertion. About 5 mm of space should be left between the chuck and the drill guide when a hole of correct depth has been drilled. Approximately 50 mm of the drill bit should extend from the chuck of the drill.

All holes must be drilled prior to the removal of the drill guide. It is not appropriate to drill one hole and then remove the drill guide for any reason. The small error created by replacing the drill guide generates an asymmetry between the probes, which may be correctable if small enough, but is unhelpful to the data gathering process.

The holes should be a snug fit, but you should not need much force to insert the probes into the holes. If you find it difficult to fully insert the probes, the holes may require further cleaning by carefully drilling out the holes.

NOTE 44: Try to avoid redrilling holes once the drill guide has been removed. The xylem fibres of some species are held under extreme tension and relax after the hole has been drilled, making the insertion of the measurement needle very difficult. In this situation, the hole will need to be reamed out by carefully running the drill back and forth through the hole to cut away the expanded fibres that encroach into the hole. Do not attempt to forcefully redrill the hole. Simply hold the drill without pressure and allow the drill bit to run in and out through the existing hole.

Photo 28: Cleaning the holes once the drill guide has been removed.

16.6.3 Drilling Tips

If using a conventional cordless power drill, best results are achieved when the power drill is held in the horizontal plane. This is because the power drill is unbalanced with the majority of the weight distributed in the handle and the battery below the drilling position. The uneven weight distribution causes the operator to gradually lower the drill.

The set of 3 holes should take over 10 minutes to drill correctly and slowly. If the guide slips or a drill bit breaks, the installation site should be discarded and a new site should be found.

Photo 29: Horizontal drilling using a conventional cordless drill.

16.6.4 Check the Holes are Parallel

After drilling all three holes, remove the drill guide and check the installation to see if the three holes are aligned axially and parallel to each other. This can be done by inserting three drill bits into the holes and inspecting them visually. A piece of 5 mm lined note paper can be a very handy guide.

Photo 30: Two methods of checking that the holes are parallel before inserting the needles.

16.7   Spacers

If the bark is thinner than 10mm, small spacers can be used so that the outer measurement point sits 2.5mm below the cambium, in the outer sapwood. Spacers can be made from the sheath of the figure-8 power cable used for charging the SFM1. Use a razor blade to cut 3 spacers the same length with squared edges on both sides.

16.8 Grease Needles

Prior to inserting the needles, use a small amount of inert silicon vacuum grease to aid installation and removal of the needles. Used in moderation it is very safe and will not affect the plant or the measurement in a detrimental way. Silicon grease will improve the thermal coupling of the needle to the sapwood and minimise the cementing action of sap and gums produced by the tree in response to wounding around the invasive holes drilled into the sap wood. This will be of significant benefit when it comes time for uninstallation.

Photo 31: A 10mm offset syringe filled with silicon grease can be used to grease the needles. Note the red spacer at the top of each needle.

16.9   Insert Needles and Attach SFM1 to Tree

If all three holes are satisfactory, the needles greased and spacers fitted if necessary, you can insert the needles. Begin by inserting the top needle first, then heater and finally the lower needle. You should only require light pressure to insert the needles into the drill holes.

WARNING 11 – Never use a hammer or other object to hammer the needles into place, this will damage the needles.

Slot the mounting bracket into the mounting slots on the back of the SFM1 to attach the instrument to the tree. Position the instrument so that a gentle curve in the cable of the measurement needles is created to take the strain off the cables. Use the mounting bracket to attach the SFM to the plant. The bracket allows for many attachment options such as: Velcro or other fabric straps, tie down/ratchet straps, screws or nails on either side, or even fencing wire.

16.10 Insulation

Generally, no radiation shielding or thermal insulation is required around the installation site.

In hot climates where the SFM1 is exposed to direct sunlight a solar radiation shield should be used to keep the logger below 60°C.

As the SFM1 is a Heat Pulse Technique, the measurement protocol involves measuring and accounting for thermal gradients before commencing the measurement process. If it is anticipated that temperatures are likely to change within the 100 second measurement cycle, reflective bubble-foil shielding can be used to insulate the needles. If temperature differences between the tree and SFM1 are expected to exceed 15°C, shielding over the probes should be installed.

16.10.1 Insulate Needles on Small Diameter Stems
If needles extend beyond the stem they must be insulated from direct sunlight. The sheath of the figure-8 power cable is ideal. Alternatively, insulating foam could be used.
Cover the full installation with aluminium foil to reflect direct radiation. The insulation will prevent heat transfer from the needles touching the aluminium foil.
For further reference, see the Small Stems Installation video before working with small stem installations for the first time.

Photo 32: Installing insulation on exposed needles extending beyond the diameter of the stem (left) and applying additional foam insulation (right).

16.11 Uninstallation

SFM1 needles are relatively easy to remove. The key is to be slow and gentle as with installation. Begin by grasping the hubs of all three needles and turning them in a block about a quarter turn anticlockwise, then a quarter turn clockwise. You should hear and feel a cracking sound as the needles break the bond with the sapwood. Remove each needle individually. Place your left-hand index knuckle against the stem to brace as a pivot point and your right hand as a guide on the cable. The right hand should not apply any pulling force as this could damage the needles.

If the needles are especially tight you may need to use an additional lever such as a flat bade screw driver. If this is required it must be used very carefully and only in short distances. Attempting to lever the needle out in a single pass with a screw driver will bend and probably break the needle.

16.11.1 Needle Removal

Begin by using a small lever or flat screw driver inserted against the edge of the epoxy base of the sensor to gently prise the needle back from the edge of the tree. If bark or cambium remain in place around the needles this can be scraped away to give access for the lever or screw driver.

Only mild leveraging force is necessary to break the seal between the needle and the sapwood. Once the seal is broken and the needle begins to move try withdrawing the needle by hand. If it is still too difficult to do by hand reposition the screw driver and continue levering the needle out and guiding the base of the needle with your other hand. Be careful not to bend or break the needle. Repeat this procedure for the remaining two needles.

Photo 33: Using a flat screwdriver to carefully prise the needle out of the tree.

16.11.2 Repair

The SFM1 needles are designed to be robust, however, they are delicate scientific instruments that must be treated with care. Uninstallation is the activity where they are most likely to sustain serious damage, especially if the tree has grown rapidly and substantially calloused around the needle hubs and/or cemented the needles into the sapwood with sap, resin and gums. Below are examples of damage that can occur if the instructions for removal are not followed with great care.

Photo 34: Broken needles.

If the needles are broken they must be replaced by a trained ICT Technician. Contact sales@ictinternational.com.au for more information.

16.12 Care & Maintenance

SFM1 Sap Flow Meters are designed to be reused in multiple installations and applications. The instrument is designed to be water proof and environmentally sealed. Firmware upgrades can be performed by the user so the instrument can always be updated with the latest features or advancements. Individual measurement and heater needles can be replaced if bent or broken for any reason. There is no reason not to expect many years of reliable service from your SFM1 Sap Flow Meter if maintained and treated well.

16.12.1 Cleaning

When the SFM1 is uninstalled, clean the needles with a damp sponge, using a mild detergent to remove any gum or tannin residue left behind from the tree. Dry the needles and store in a cool dry place until you next require the instrument.
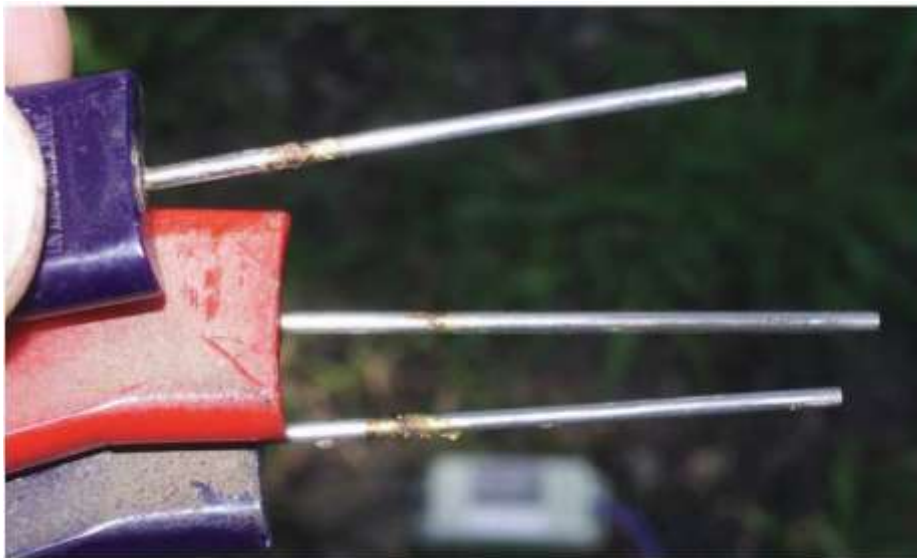
Photo 35: Needles that require cleaning.

16.12.2 Storage

The SFM1 is shipped in a custom designed storage box. This box be should be kept and used to store the SFM1 when not in use. This will protect the needles from damage and make the instrument easy to store neatly on a bookshelf or cupboard ready for the next deployment.

If the SFM1 is being stored for a long period of time, the internal battery should be charged every 3 to 6 months. Make sure that the instrument is not logging and is turned off after being charged.

17   Data Storage & Download

Data is stored on a removeable MicroSD card.
Data can be downloaded via USB cable, wireless RF using a MCC, or by removing the MicroSD card.

17.1   Data Storage Capacity

The supplied MicroSD card is 4GB. In practical terms, when the SFM1 is logging all parameters and diagnostics, at a 10-minute logging interval, this is sufficient for hundreds of years of continuous measurement.

If logging in Raw Needle Temperature mode, 4GB will hold about 80 years' worth of measurement data.

Larger MicroSD cards, up to 16GB, can be used – however there is generally no need for this unless an experiment is expected to take over 400 years.

17.2   MicroSD Card Format

MicroSD cards must be FAT32 formatted. Any off the shelf MicroSD card can be used.

The MicroSD card can be removed from the instrument and inserted into a computer to copy the data file (csv) without having to stop the instrument logging.

17.3   Data File Name

The data file is automatically generated by the SFM1 using the following format: instrument_serial_number.csv e.g.: SFM1F813.csv. The serial number is a uniquely identifier for each instrument and contains specific information about the date of manufacture and production run. Please provide the serial number to ICT International with all support inquiries.

The serial number is also included in the header of the data file and is on a sticker on the back of the instrument.

17.4   Data File Format
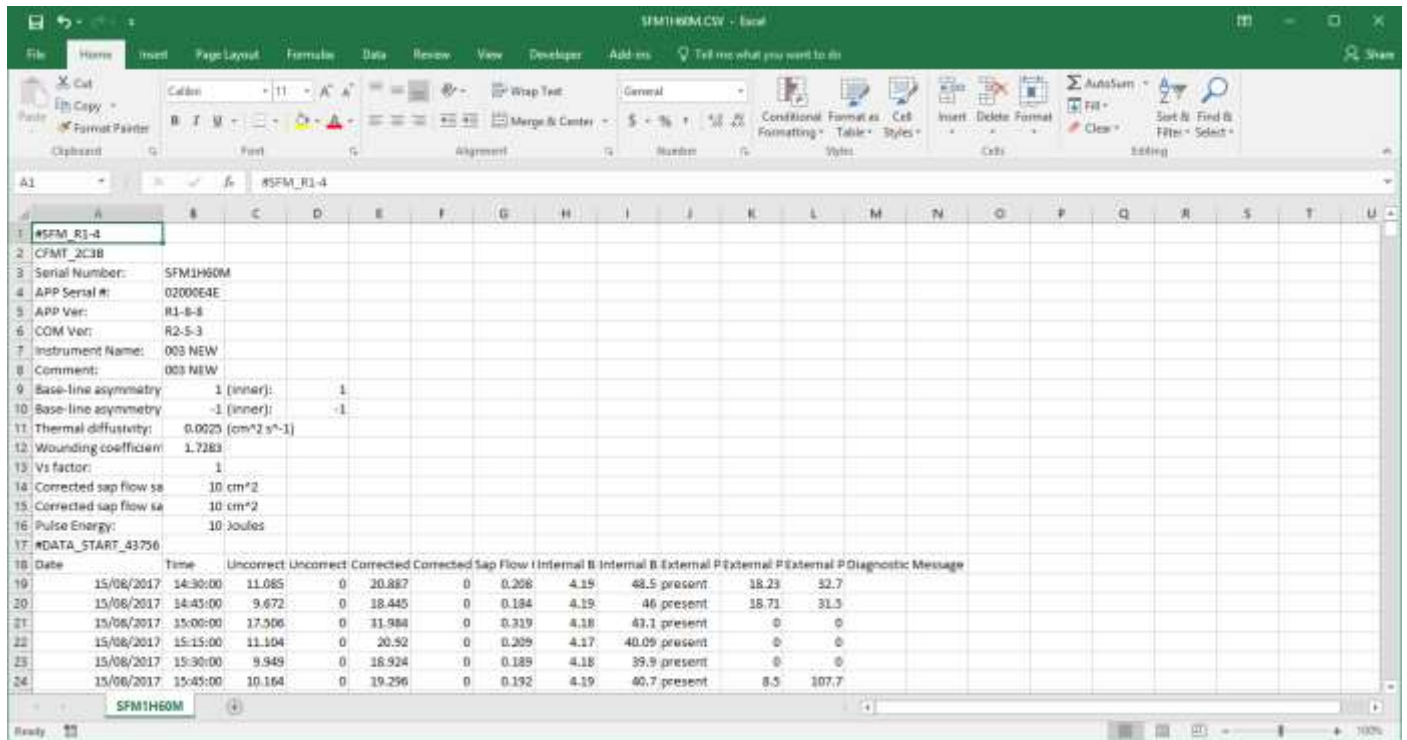
The SFM1 stores data in one of two file formats, *.csv or *.bin. The decimal delimiter (. Or ,) is based on the regional settings of the user's computer.

If the computer's regional settings are different to the Sap Flow Meter, a warning message will be displayed.

17.4.1 Sap Flow Mode

Sap Flow Mode, the standard operating mode for the SFM1, records data in .csv format. These files can be opened in Excel, ICT Combined Instrument Software, or Sap Flow Tool.

This file contains sap flow measurements and associated raw data. The file also contains a header with all the instrument parameters.

Figure 20: Data file header, as displayed in Excel.

17.4.2 Needle Temperature Mode

Raw Temperature Data files have the file extension *.BIN and are used for logging the high temporal frequency (up to 30Hz) needle temperatures that enable advanced data processing using any heat pulse algorithm. Because the Raw Temperature Mode records large volumes of data, potentially 30 readings per second for 300 seconds per measurement, the data is stored in a binary (*.BIN) format. This file can only be opened in SFT software for analysis. These files have the potential to be very large, depending on the logging interval and longevity of the installation.

.BIN files should be download by removing the MicroSD card from the instrument.

SD Card Logging Options were covered in Chapter 15.5.6.

17.5 Downloading Data

Data can be downloaded in a number of ways. The simplest is use the Download button in the Data tab. Another option is to use the Manage SD function. This allows you to select a file to download, rename or delete, and it allows you to select a location to save the data file.
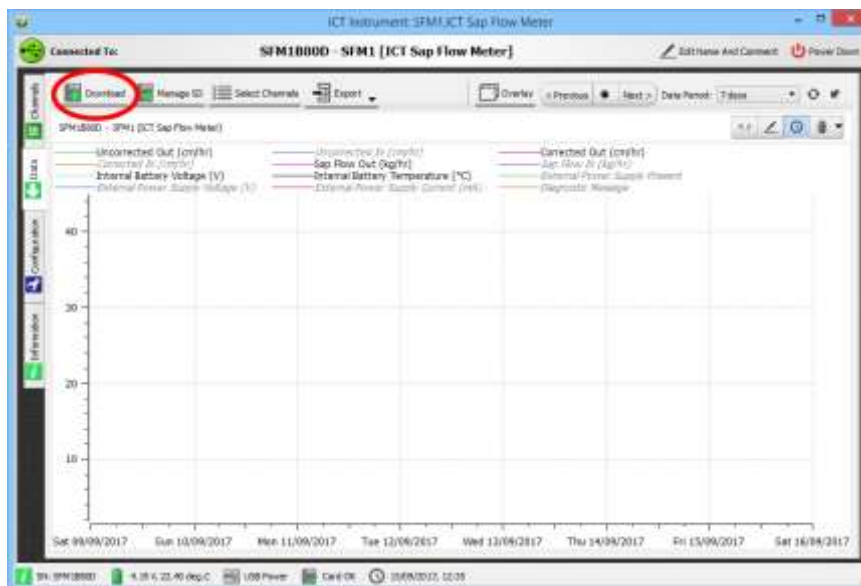
Figure 21: The Download button.

Figure 22: Manage SD – Download File. This allows you to download the data file to a location of your choice.

After downloading the data file from the instrument, the data file can be deleted from the MicroSD card if the experiment is finished, or renamed if you wish to keep a copy on the MicroSD card.
If you delete or rename the data file, a new data file will be created next time the instrument is used.
If you do not delete the data file, data will be appended to the data file and will continue to be logged as usual.

17.5.1 USB Cable
A standard USB-Mini USB cable is provided for instrument configuration and data download. This is not a proprietary cable, any Mini-USB cable can be used.

17.5.2 Wirelessly via MCC

A MCC-Mini can be used to download data from an instrument in the field from up to 250m with standard antennae. Connection procedure was covered in Chapter 13.2.

17.5.3 Download via USB/SD Card Adaptor

The SFM1 data can be downloaded by removing the MicroSD card using a USB Adaptor (supplied by ICT or available from electronics and computer stores) or MicroSD to SD card adaptor.

Open the USB Port Cap to access the MicroSD card. The MicroSD card is secured by a spring locking mechanism, press on the edge of the card to release the spring then remove the card. A pair of forceps or tweezers is very convenient for extracting and inserting the card.

Photo 36: Removing the MicroSD card using a pair of tweezers.

18   Data Analysis

Data recorded in the standard Sap Flow Mode is saved in a Comma Separated Value (*.csv) file. Data recorded in Needle Temperature Mode is saved in *.bin format.

CSV files can be opened in Excel, CIS, Sap Flow Tool, or other data analysis software. BIN files can only be used by Sap Flow Tool. CIS and Sap Flow Tool provide the ability to compare measured sap flow data with other measured parameters, such as Stem Water Potential, Solar Radiation, VPD, or Soil Moisture. This allows for easy evaluation of these environmental interactions on plant water use.

18.1   Analysis of Raw Heat Pulse Velocity

The Raw Heat Pulse Velocity is a measure of the heat movement through the woody matrix of the plant stem. The velocities measured do not directly relate to sap velocity. This data must first be corrected for wounding, thermal diffusivity, and asymmetry before it can be used for quantification of the sap velocity. Nevertheless, the diurnal trends are still very meaningful and can be interpreted in terms of the timing of events that affected the plants use of water.
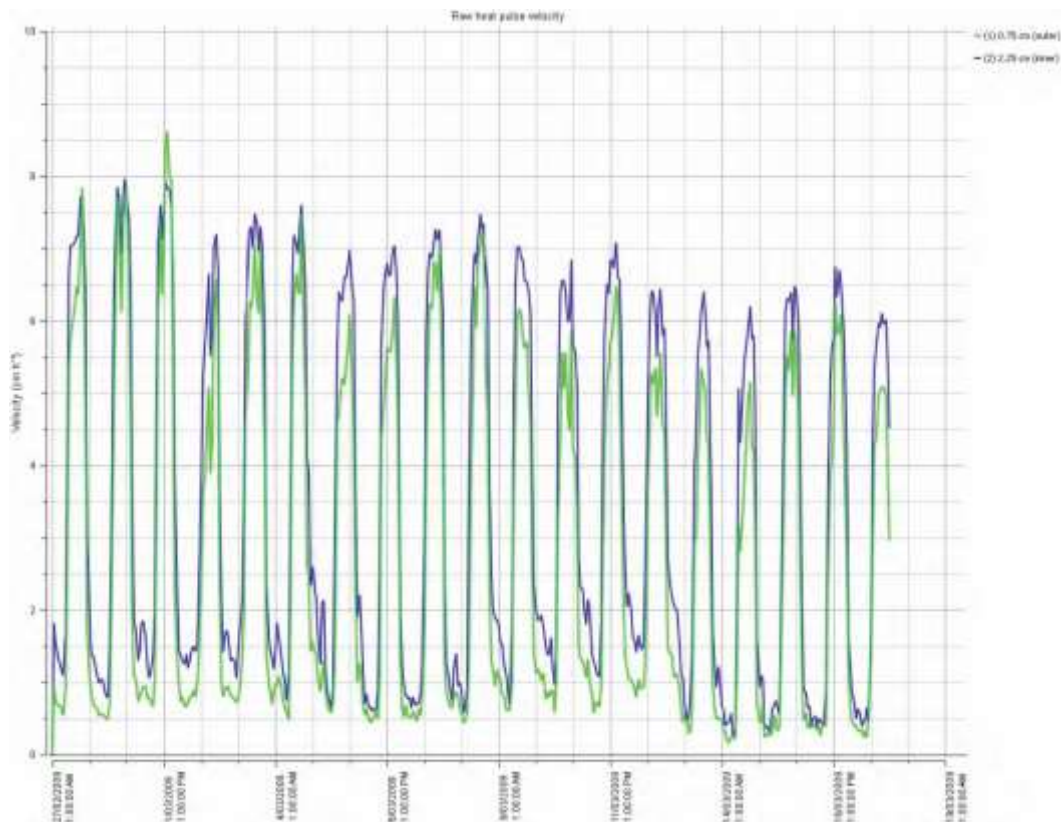
Figure 23: Raw Heat Pulse Velocity data is relative in nature, and can be used qualitatively but not quantitatively.

18.2 Uncorrected Sap Velocity

Uncorrected Sap Velocity (Uncorrected In/Uncorrected Out) is a measure of the speed at which water moves through the water conducting xylem of the plant. These parameters have some basic processing applied to them to convert from needle temperature to sap velocity, but require further processing to produce corrected values.

Required parameters include: tree diameter, bark depth, sapwood thickness, probe spacers, measurement offsets, thermal diffusivity, wound diameter, sapwood fresh and dry weight, and sapwood fresh volume.

ICT Combined Instrument Software's SFM Water Usage mode provides a parameter editor in which these values can be entered to automatically calculate corrected values.
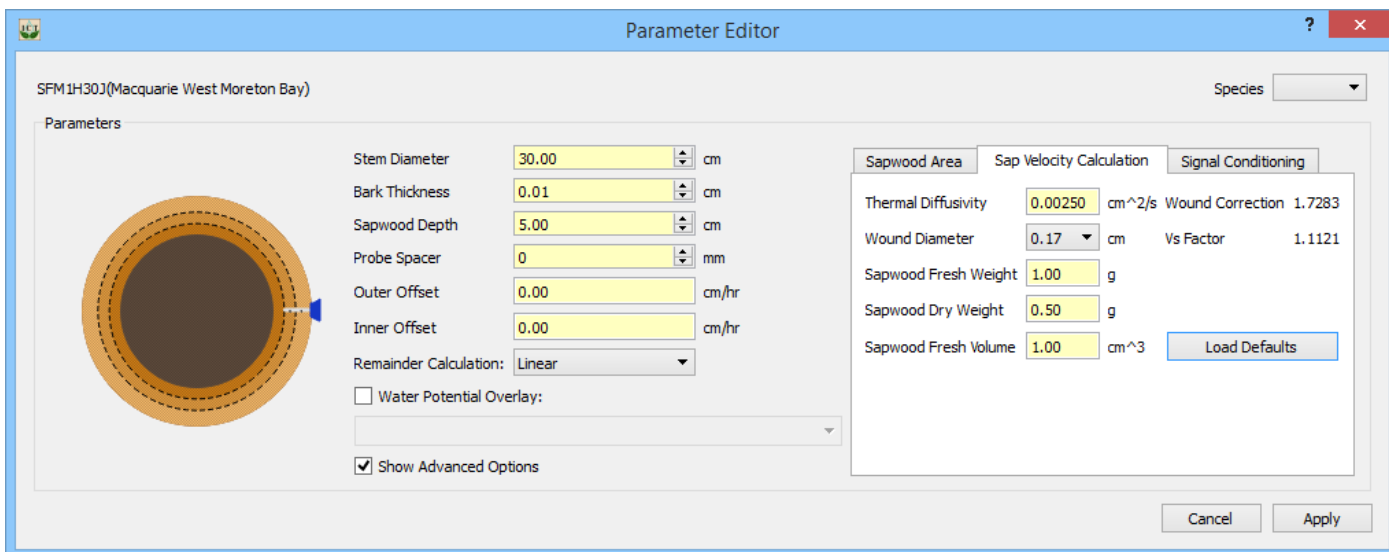
Figure 24: CIS – SFM Water Usage Mode Parameter Editor. Wound Correction Factor, Vs Factor and sap wood areas are calculated automatically using the entered values.

Sap Flow Tool provides similar and extended functionality for the analysis of sap flow data.

18.3 Corrected Sap Velocity

Corrected Sap Velocity is a quantitative measure of the speed at which water moves through the water conducting xylem of the plant. Using SFT Software it is possible to analyse the velocity and the timing at which velocities of water movement occurred and changed within the tree. In addition to this, a simultaneous sap velocity profile graph can be overlaid on the sap velocity data to characterize the radial gradient of water movement from the outside of the tree in the actively conducting xylem as its water conducting capacity degrades as the xylem ages towards the sap wood - heartwood interface; at which point the heartwood ceases to be functional in conducting water. The diurnal changes can be used to understand changes in access to water. The combined interpretation of the velocity at which water moves through the tree at different times throughout the day and where the water is coming from radially within the tree allows powerful interpretations about plant water stress.
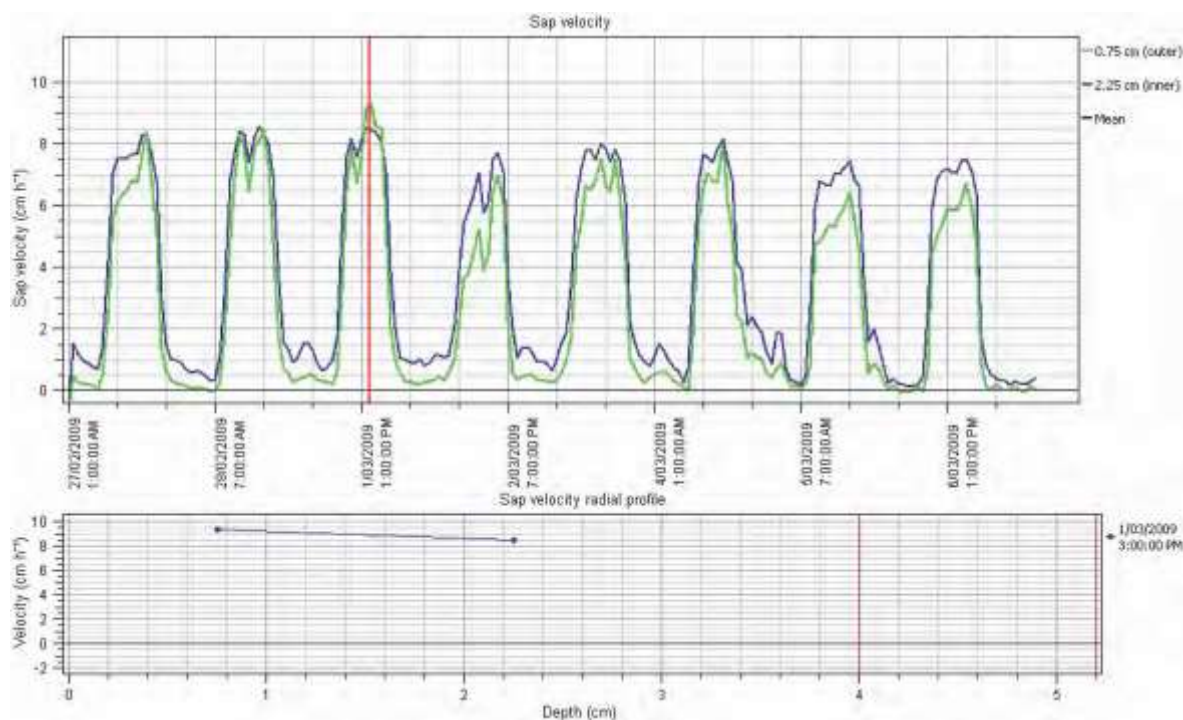
Figure 25: The combined analysis of sap velocity simultaneously overlaid with radial profile of sap velocity.

Corrected In and Corrected Out values are automatically calculated and logged based on the values entered in the Configuration tab of the SFM1, covered in Chapter 15.5.5.

18.4   Volumetric Sap Flow

The Sap Flow rate is a corrected, volumetric rate at which water moves through the plant. It displays the volume of water used by the plant at any given time throughout the diurnal pattern. The sap flow rate also enables the accurate determination and quantification of nocturnal sap flow or night time water use.

Sap Flow In and Sap Flow Out (kg/hr) is based on values entered in the Configuration tab, as with Corrected Sap Velocity.
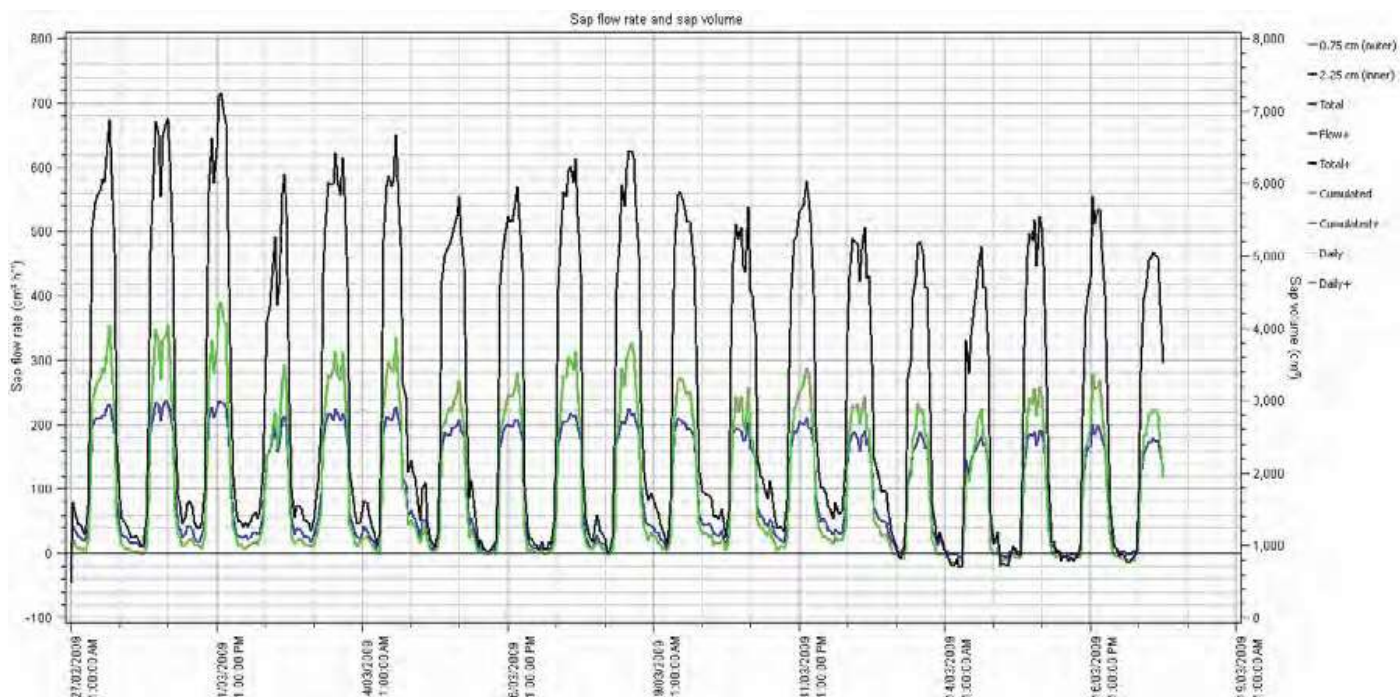
Figure 26: Sap Flow Rate and Sap Volume, from Sap Flow Tool.
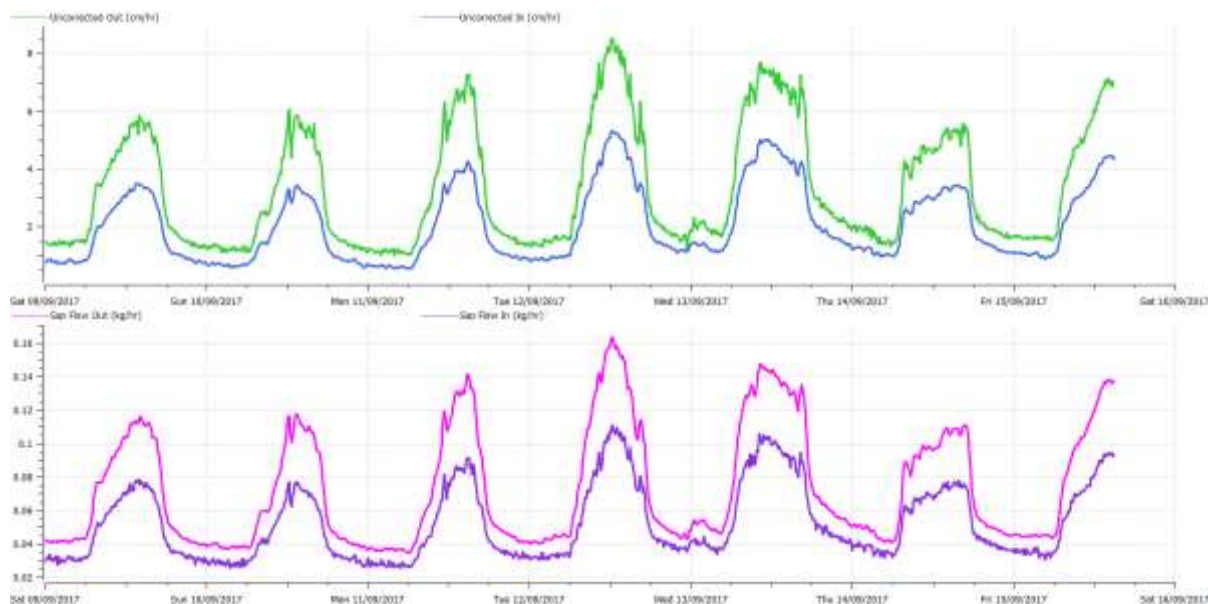
Figure 27: Sap Flow Rate and Sap Volume, from ICT Combined Instrument Software – Dataview.

18.5   Cumulative Sap Flow Analysis

Volume of water used throughout the a 24-hour period can be calculated in SFT, and is displayed automatically in SFM Water Usage mode in CIS.
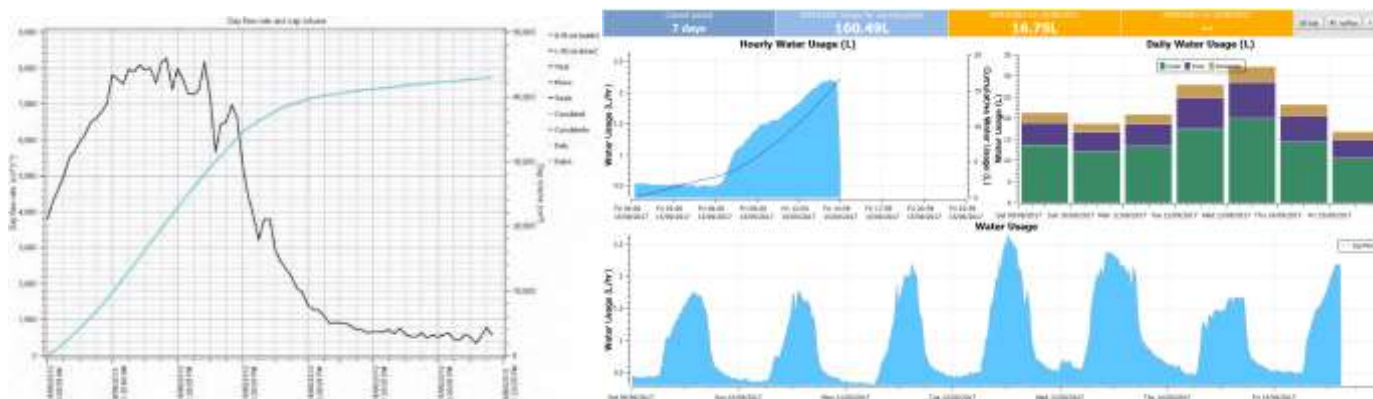
Figure 28: Cumulative Sap Flow in SFT (left, light blue line) and in CIS (right, top left graph, dark blue line).

18.6   Environmental Sap Flow Analysis

Sap Flow data is an extremely powerful tool in understanding the complex interrelationship between a plant and the environment. A Tree (or plant) is the ultimate transducer. It synthesizes and integrates all of the abiotic variables of the surrounding environment that are acting upon it and provides a single measurable output that reveals how these inputs have affected its growth.

The continuous, non-destructive, high temporal, diurnal sap flow trace can be considered analogous to the Electrocardiogram (ECG) of a human heart. As external stimuli are imposed on the body, or, in this case, the tree, the sap flow rate will increase or decrease much like an Electro-Xylem-gram (EXG).

As light increases (given all other parameters remain the same and water reserves are adequate to meet supply) so too will the rate of sap flow of the tree. As Light decreases, so too will the sap flow. This is because the demand for the exchange of water for CO_2 to perform the process of photosynthesis is decreased. Because of this intimate interrelationship between the plant and its environment, sap flow must be interpreted not in isolation, but in concert with meteorological and environmental parameters, to be able to isolate and determine both the cause and effect of the changes in the growth of the tree.

This can be done by overlaying data from a weather station or from other environmental sensors such that data trends in both sap flow and conditions effecting sap flow can be evaluated.

20   Measuring Zero Flow

Performing a cut stem experiment is the ultimate measure of zero flow. The stem should be cut during the day and during its maximum sap flow rate. Cut the stem below the measurement needles. The more xylem left between the needles and the cut the longer it takes for the flow to reach zero due to the capacitance of the xylem.

Once the tree exhausts the water reserves stored in the xylem and the flow reaches zero, continue to measure for 30 minutes to 1 hour to ensure a definitive data set of stable zero flow data. If the needles have been installed symmetrically, the flow recorded will indeed zero within a tolerance of +/- 0.5 cm hr^{-1} (the published limits of accuracy for the SFM1). In many cases it will be more accurate than this. If the flow does not reach zero or goes below zero then there is an asymmetrical arrangement of the measurement needles i.e.: both needles are not 5mm above and below the heater.

20.1   Cut Stem Analysis

For the purpose of comparison this experiment was performed on two different species:

Callitris glaucophylla and *Eucalyptus blakelyi* with different water use rates and sap wood thicknesses.

20.1.1 *Callitris glaucophylla*

Species: *Callitris glaucophylla*
Sensor installation aspect: West/South West
Diameter: 11.3 cm
Bark thickness: 6 mm
Sapwood thickness: 25 mm
Heartwood Thickness: 20 mm
Wounding: 0 mm radius
Density: ??
Thermal Diffusivity: ??

Average night time offset:	Inner: 1.88 cm hr^{-1}	Outer: 1.32 cm hr^{-1}
Raw Heat Pulse velocities before Cutting:	Inner: 20.53 cm hr^{-1}	Outer: 24.94 cm hr^{-1}
Raw Heat Pulse Velocity after cutting:	Inner: -0.54 cm hr^{-1}	Outer: 0.49 cm hr^{-1}

Photo 37: Cut stem *Callitris glaucophylla*.

Sap Flow was measured for 10 days to provide a stable diurnal sap flow data set prior to severing the stem. Subsequent to cutting the stem the zero flow of +0.49 cm hr^{-1} on outer and -0.54 cm hr^{-1} on inner was reached within 30 minutes of cutting.

These values are within the stated accuracy of the instrument suggesting the installation was symmetrical. Now, with this confirmation, the preceding 10 days of data can be interpreted. It shows that the initial days recorded were in fact going to zero at night and, subsequent to this period, when the data was not reaching zero at night that the tree was in fact using water at night.

It cannot be confirmed from this data if that water was transpired through the leaves or used for hydraulic refilling of the vessels. Nevertheless, the data can be verified as accurately recording a physiological process.
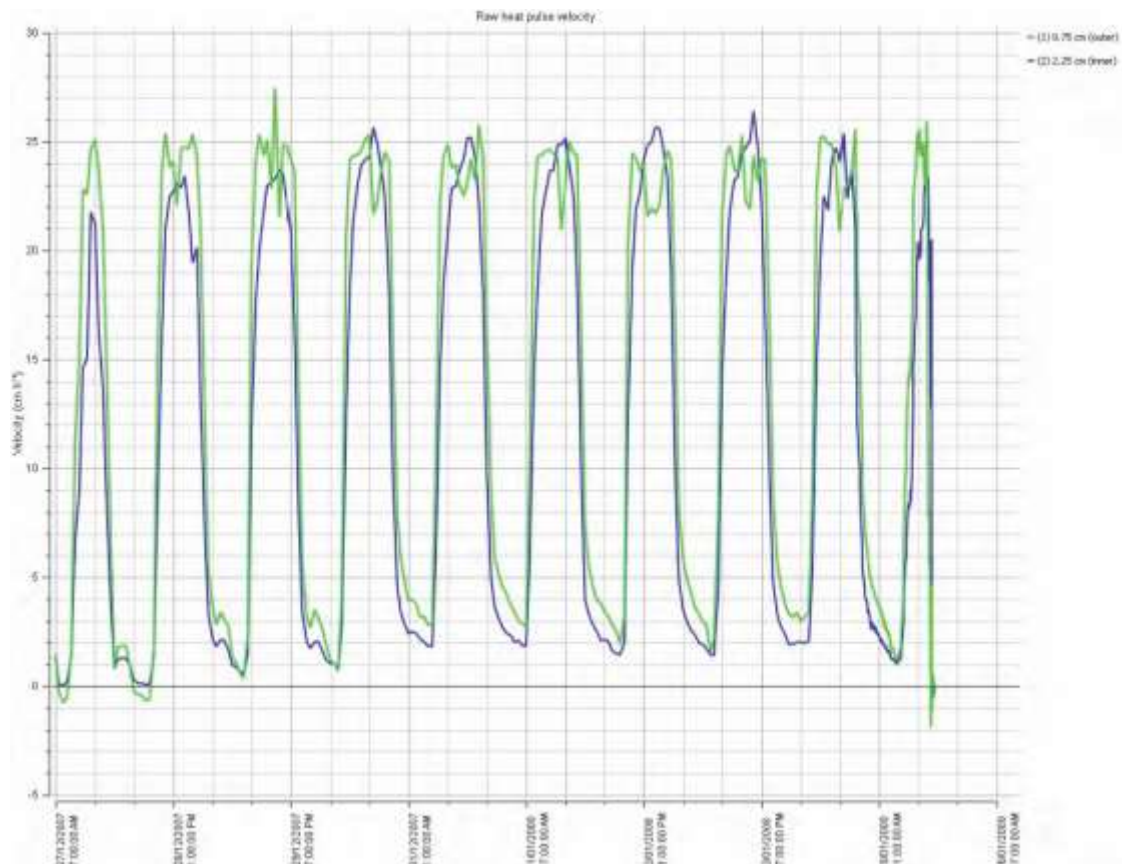
Figure 29: 10 days of stable sap flow data for *Callitris glaucophylla* prior to severing the stem.
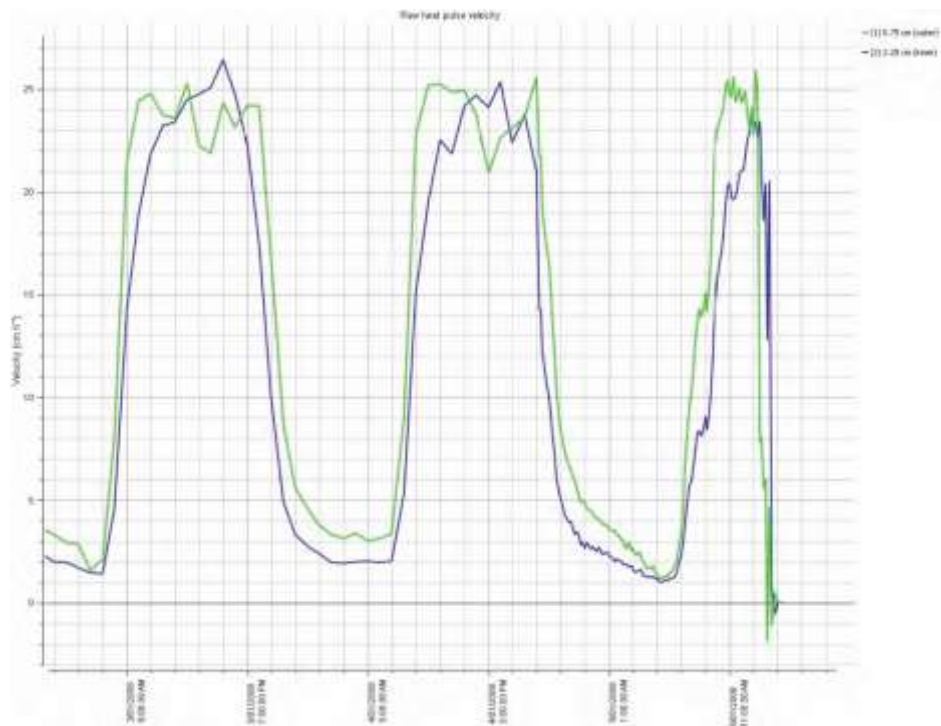
Figure 30: The immediate cessation of sap flow for *Callitris glaucophylla* upon cavitation caused by severing the water column of the tree.

Figure 31: Steady absolute Zero Flow state reached after complete severing of xylem of *Callitris glaucophylla.*

20.1.2 *Eucalyptus blakelyi*

Species: *Eucalyptus blakelyi*
Sensor installation aspect: East/South East
Diameter: 12.2 cm
Bark thickness: 6 mm
Sapwood thickness: 6 mm
Heartwood thickness: 30 mm
Wounding: 1 mm radius
Density: ??
Thermal Diffusivity: ??

Average night time offset:	Inner: -1.48 cm hr^{-1}	Outer: -1.49 cm hr^{-1}
Raw Heat Pulse velocities before Cutting:	Inner: -1.52 cm hr^{-1}	Outer: -11.78 cm hr^{-1}
Raw Heat Pulse Velocity after cutting:	Inner: -1.52 cm hr^{-1}	Outer: -0.53 cm hr^{-1}

Photo 38: Cut stem *Eucalyptus blakelyi*.
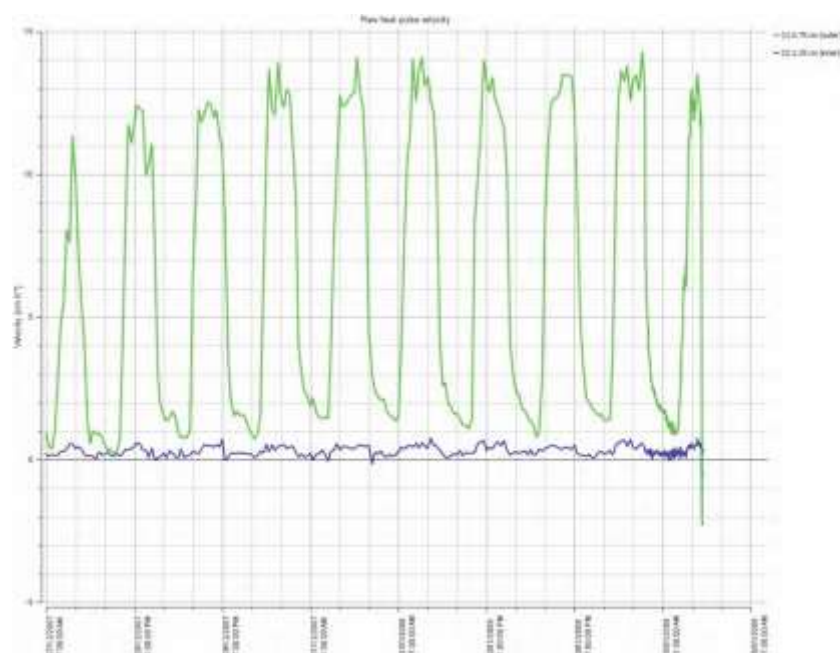
Figure 32: 10 days of stable sap flow data for *Eucalyptus blakelyi* prior to severing the stem.
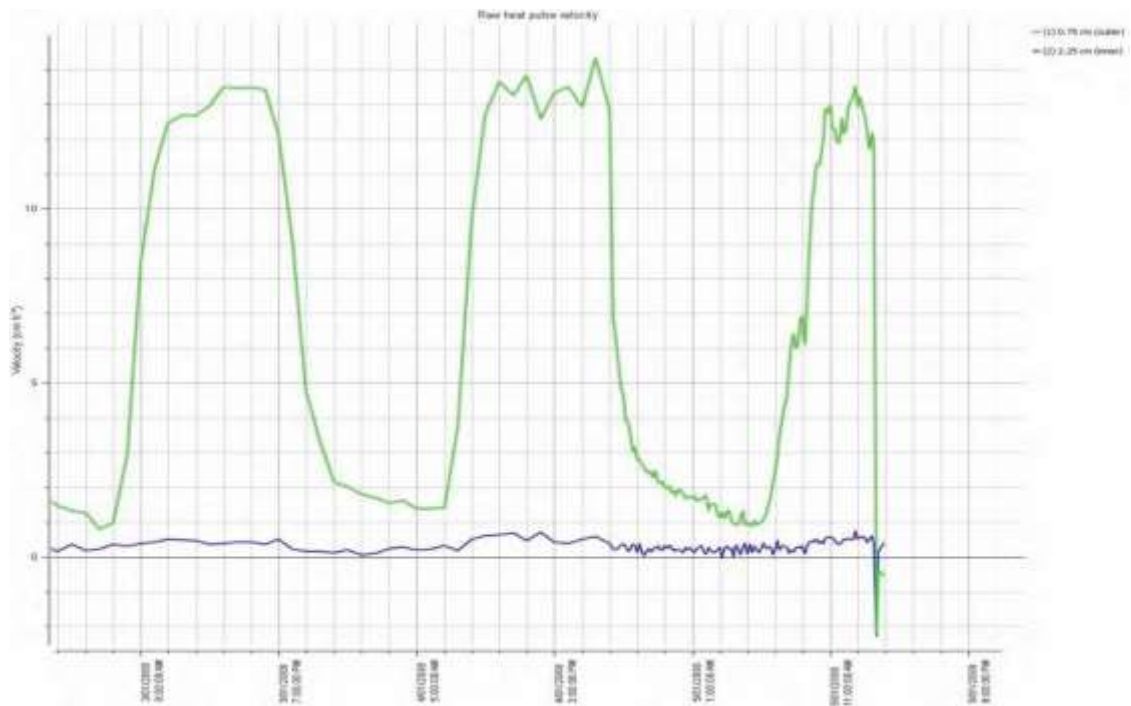
Figure 33: The immediate cessation of sap flow for *Eucalyptus blakelyi* upon cavitation caused by severing the water column of the tree.
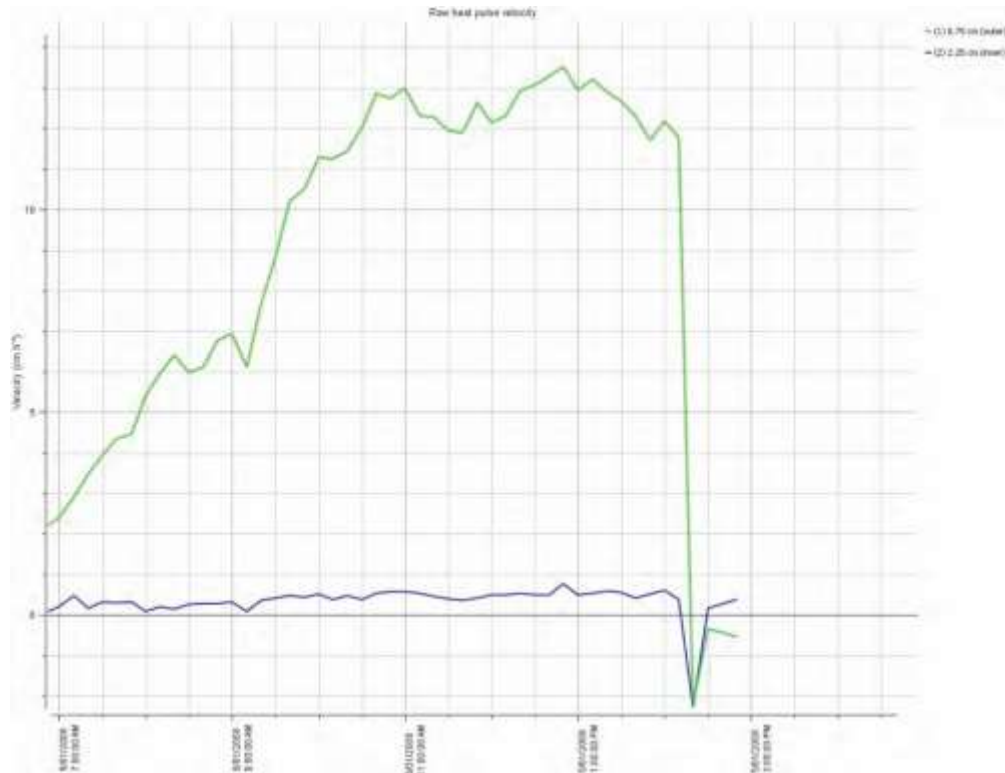
Figure 34: Absolute Zero Flow state reached after complete severing of xylem of *Eucalyptus blakelyi*. Note the negative spike immediately after severing as the values come to equilibrium following the next measurement.

E. blakelyi had a much higher heartwood percentage than sapwood with a hollow pipe in the middle of the tree. The narrow sapwood explains the noisy flat line data that shows no diurnal pattern recorded for the inner thermistor located in heartwood. The heartwood also consisted of very dense non-conducting xylem with fissures of open air voids emanating from the hollow pipe at the centre of the tree.

Photo 39: Stem diameter, *Eucalyptus blakelyi*.

Photo 40: Sap Wood thickness, *Eucalyptus blakelyi*.

21   An Ecophysiological Framework for Interpreting Sap Flow Data

20.1 Example Sap Flow data and scenarios

The following examples show Raw Heat Pulse Velocity (HPV) data from the stems of Eucalyptus trees. They are designed to provide background reference to aid in the interpretation of sap flow measurements and troubleshooting when installing SFM1 Sap Flow Meters.
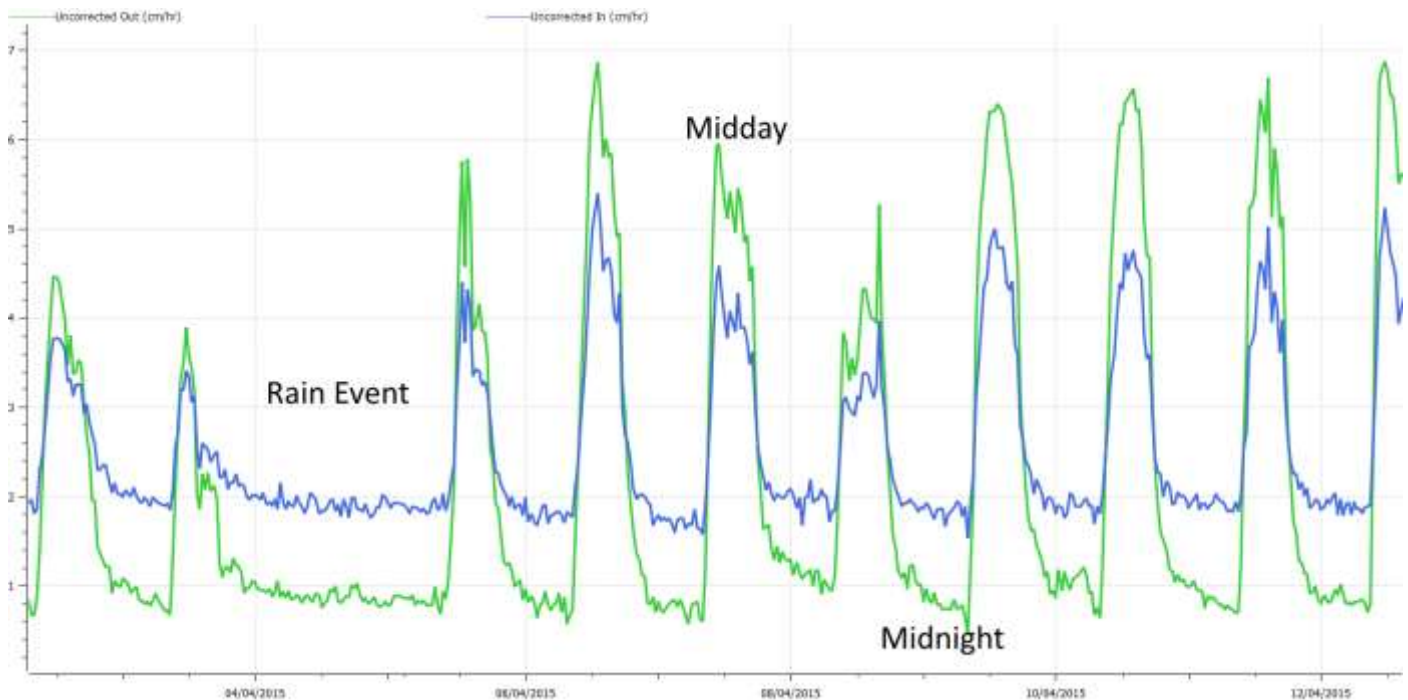
Figure 35: A typical diurnal heat pulse velocity pattern of a *Eucalyptus camaldulensis* with very 'clean' HRM data and no obvious problems; needles well in conducting sapwood. Zero flows are experienced at night time with fluctuating peaks throughout the day in response to changing light conditions and evaporative demand. In this example, the effect of a rainfall event on sap flow can be clearly seen.
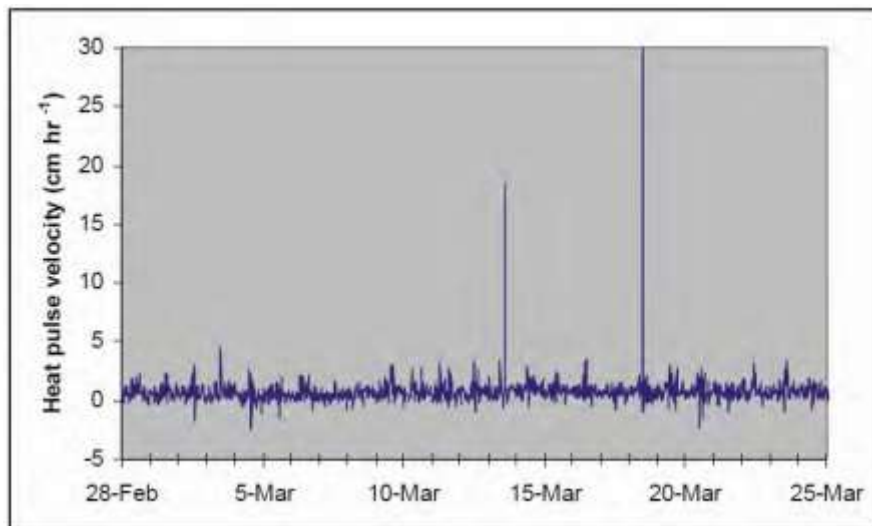
Figure 36: Data from probes installed in wood with poor hydraulic conductance: This is typically what you might see if the measurement points are located in non-conducting heartwood or cambium/bark tissue. There is only a very slight diurnal pattern. Note also that minimum HPV is very well aligned with the zero line, indicating that probe alignment in this example was quite good, assuming there was next to zero sap flow at this measurement point.
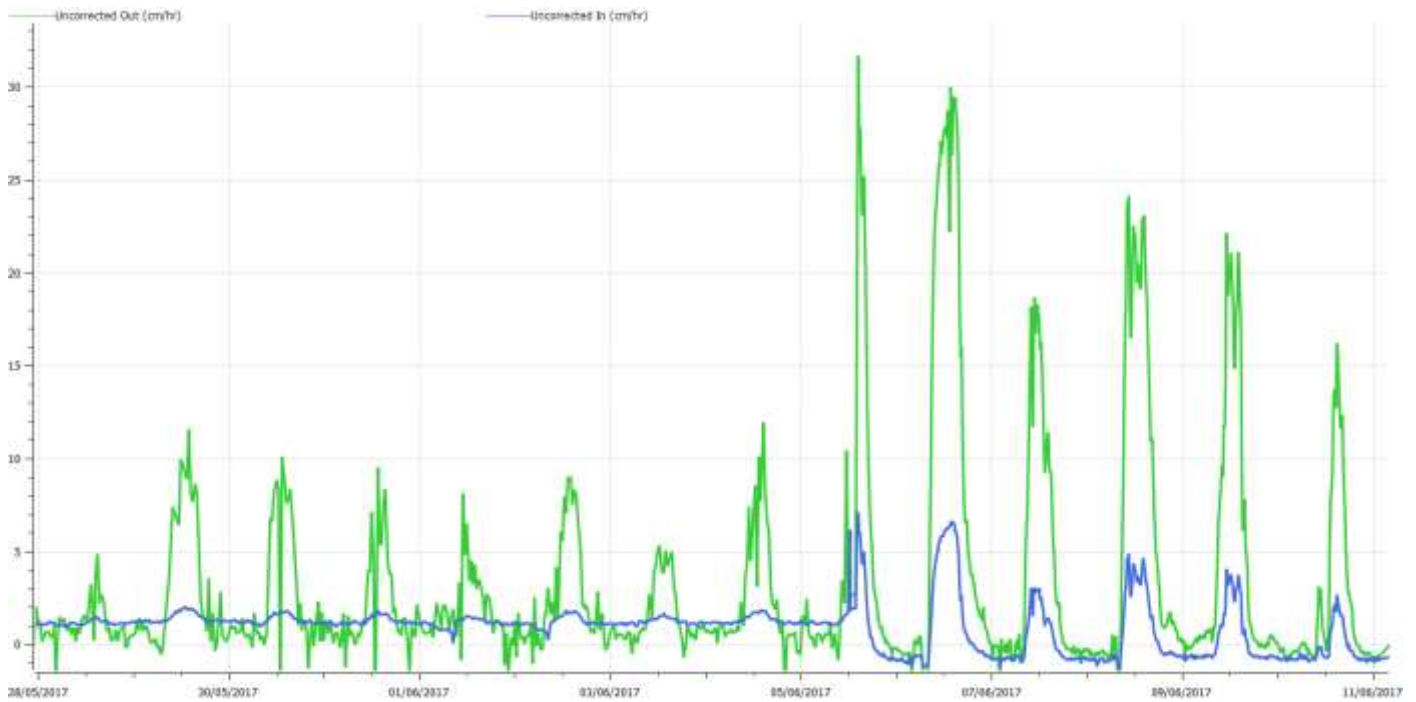
Figure 37: Data from a sensor that had developed a significant wound around the drill holes, followed by data obtained from the same probe set after it was re-installed nearby on the same stem: Note how wounding has severely reduced the magnitude of HPV measurements and dampened the diurnal pattern compared to the 'true' measurements from the fresh installation.
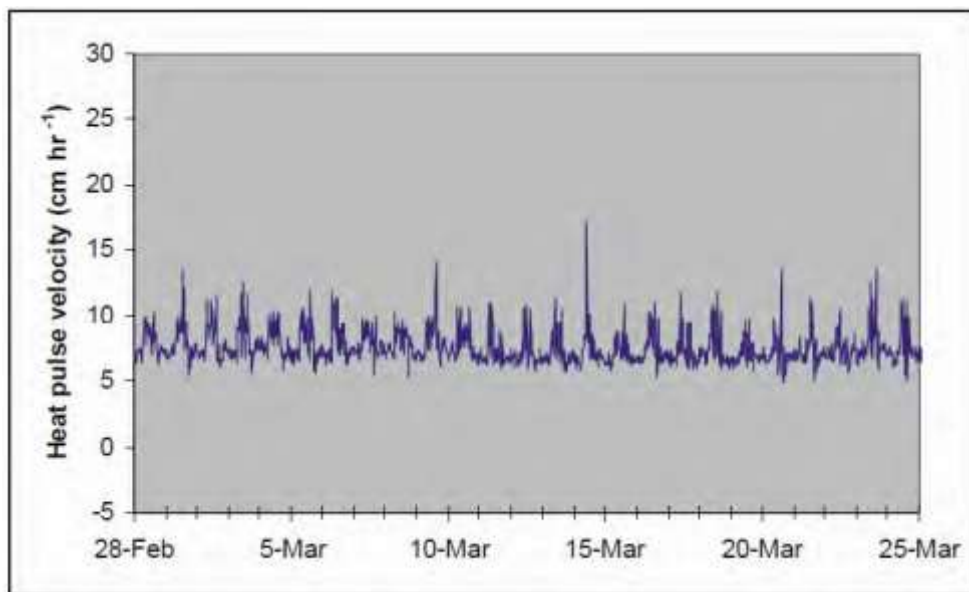
Figure 38: Data from a sensor that has been poorly installed such that one or more probes is badly out of alignment, resulting in an elevated (or decreased) baseline during periods of zero or near zero sap flow: The HRM has a provision to correct for bad probe spacing, but only to a certain extent (see Burgess et al. 2001). Nominally, probe spacing errors leading to baselines > +5 or < -5 cm hr^{-1} cannot be corrected and reinstallation is necessary (such as in the case above).
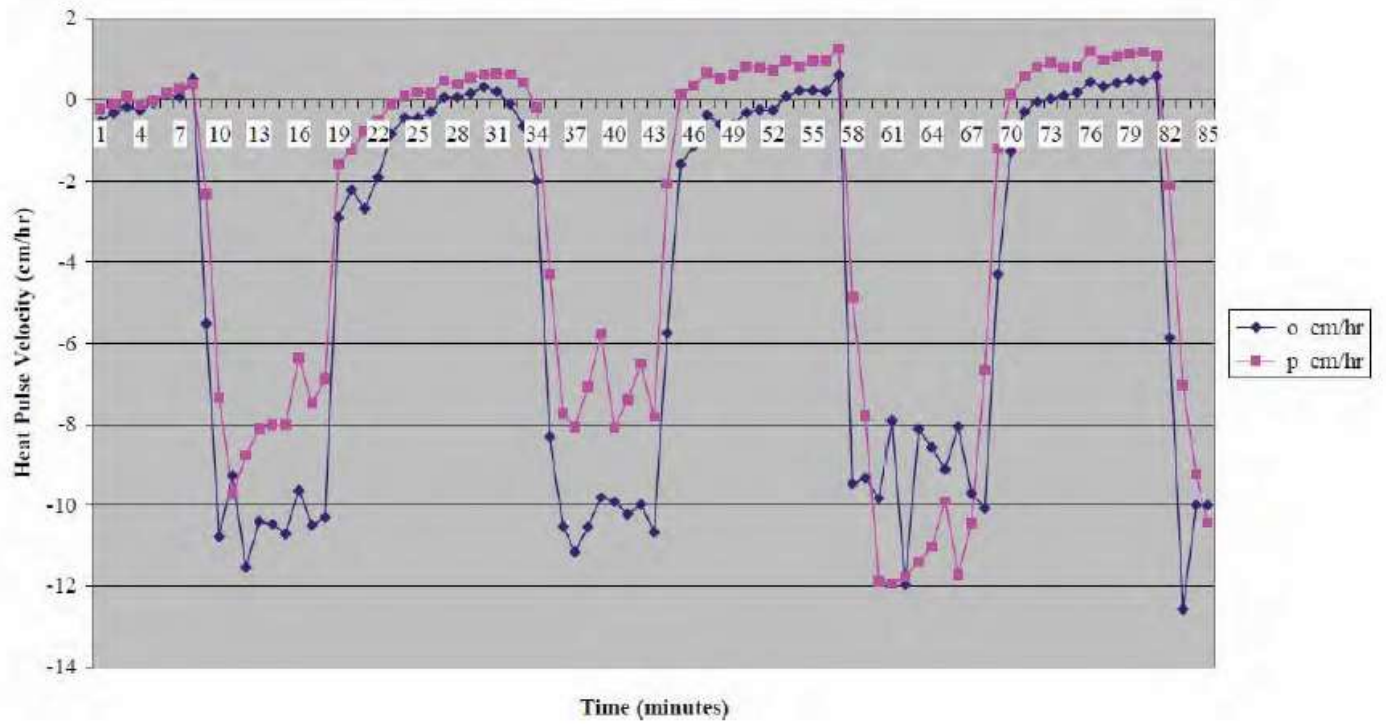
Figure 39: Example of SFM probes installed upside-down. The diurnal pattern is correct, except the values are negative. The upside-down pattern is observed when the downstream temperature probe is installed in the upstream position in the plant and vice versa. These problems are easily fixed, and furthermore, the data collected is not erroneous other than being inverted (also easy to fix as long as the user knows which way is up, particularly when working with roots!)

22   Frequently Asked Questions - FAQs

1) Will sap, resin or latex exuded by the tree damage the measurement needles?

Answer: NO. The needles are made from completely sealed stainless steel. Sap, resin & latex will not damage the needles.

2) How do you turn off one of the measurement points along the needle?

Answer: The SFM1 is designed to provide two points of measurement radially across the sapwood. Either the Inner or the Outer Measurement point can be turned off in Configuration - SD Card Logging options in CIS. This was covered in Chapter 15.5.6.1.

3) What does it mean if the value of the Outer measurement point is greater than the Inner measurement point?

Answer: This is typically what you would expect to find in a correctly functioning SFM1 Sap Flow Meter, installed in a healthy plant. Sap flow is not uniform across the sapwood. A radial gradient exists where sap flow is often highest on the outside of the stem in the young sapwood and generally decreases to zero as it reaches the heartwood.
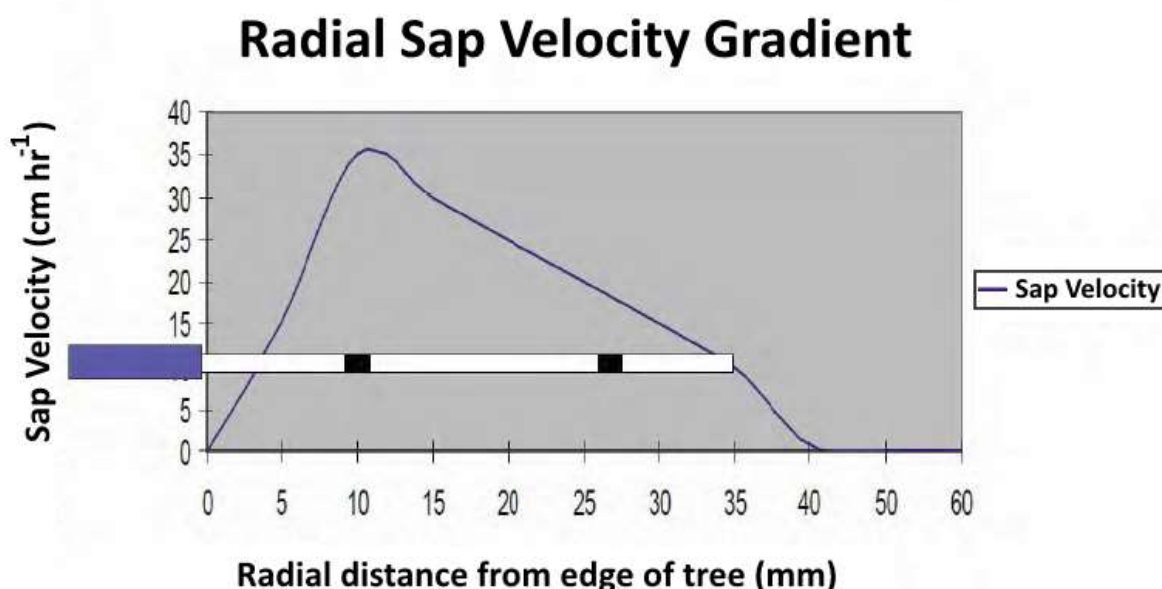
Figure 40: Example of a Radial Sap Velocity profile and how the positions of the SFM1 Needles characterise the radial gradient.

4) What does it mean if the Inner Measurement point is greater than the Outer Measurement point?

Answer: It is likely that the Outer Measurement point is not located properly in the sapwood. This may be due to an insufficient depth of bark being removed from the tree prior to installation. The sensor should be removed and re-installed.

5) What is the maximum and minimum sap velocity range for the SFM1 Sap Flow Meter?

Answer: The HRM principle is based upon symmetrical measurement geometry. Theoretically, the SFM1 has the range and resolution to accurately measure positive flows up to 100 cm hr^{-1} and negative flows down to -100 cm hr^{-1}. This has been empirically tested with a lab based calibration protocol using a high-pressure flow meter to push water through a cut stem segment at a range of flow rates up to 100 cm hr^{-1}.

6) What is an expected range for sap velocity measurements in plants?

Answer: Sap velocity will vary significantly between species, within species, between sites, within sites and diurnally within individual trees depending upon the prevailing environmental conditions. Realistically a maximum positive sap velocity in any plant will be in the range of up to 60cm hr^{-1}. However, as a huge generalization, velocities of between 4 to 40cm hr^{-1} account for approximately 80% of a plants water use/sap flow. Negative flows would rarely be expected to reach -10cm hr^{-1}.

7) What maximum temperature rise is required to ensure good data using the HRM Principle?

Answer: A temperature range between 0.5°C and 1.5°C is recommended. A Maximum temperature rise of 0.3°C may also be adequate to produce a good measurement using the SFM1. However, at this low level, any ambient thermal gradient could overwhelm the signal, so insulation around the stem is required. Below this level, even with insulation, the signal is too weak; above this the temperature unnecessarily accelerates the wounding process reducing the longevity of the installation and may damage the plant. A temperature rise of 0.7°C to 1.0°C is ideal.

8) What is a good range for the temperature ratio to ensure good data?

Answer: The ratio itself is not a good indicator of the likely validity of the data. Only the temperature rises will indicate reliable or unreliable data, taken together with the way they vary across the day. Very low rises will generally give rise to more unreliable data. However, it should be remembered that a low rise in the lower (Upstream) needle is a normal and necessary condition during high positive flow rates. Low rises in both needles simultaneously should give rise to concern. If this happens frequently the needles may need to be reinstalled.

9) What is wounding?

Answer: A wound is the plants response to drilling holes into the sapwood of the tree. The xylem cells close up to prevent further infection and begin the healing process.

10) What affects wounding?

Answer: The degree of wounding (thickness of the scab) and wound response (the time taken to produce the wound) is usually species specific and can also be site specific. One thing that does accelerate the wound response is the amount of heat used and the frequency of measurement. Always try to keep the energy input level as low as possible to minimise the wound response. This will increase the longevity of each installation and allow accurate data to be collected for a longer period between installations.

11) How do you know if the wounding affect has become too great to collect accurate data?

Answer: If the sap velocity begins to exhibit a continual decrease in the overall diurnal trend over successive days compared to previous data, compare these results against other trees in the measurement area. If none of the other trees exhibit a similar pattern and the maximum sap velocity values begin to approach zero, this is a strong indication that the wound has exceeded the maximum limit of 3mm and the sensor needs re-installing.

12) How many days data storage does the SFM1 have when logging at 10-minute interval?

Answer: The SFM1 is supplied with a 4GB MicroSD Card. A 4GB MicroSD card has sufficient capacity to store a date/time stamped, 10-minute temporal resolution data set consisting of all measured and calculated ratios and sap flow parameters for hundreds of years. Larger capacity MicroSD cards can be used if necessary.

13) What is the resolution of the digital SFM1 Sap Flow Meter?

Answer: The SFM1 is a dedicated digital Sap Flow Meter. The SFM1 incorporates the very latest technology in low noise differential amplifiers (op-amps) and Analogue to Digital (A/D) converters which form the front end of the microprocessor that drives the Sap Flow measurement. The microprocessor uses 24-bit resolution that produces a 0.0005°C (0.01 cm hr^{-1}) measurement resolution.

14) Can I force the Sap Flow Meter to fire a pulse more frequently for testing purposes even though I know the resulting sap flow data will not be meaningful?

Answer: Yes. Set the SFM1 to Manual Measurement mode and click the Start button (Chapter 15.5.1.1).

15) Can the SFM1 perform CHPM sap flow measurements?

Answer: Yes. Place the Sap Flow Meter in Needle Temperature mode and collect Raw Temperature data. Set the SD Logging Options for Raw Temperature to 3 measurements per second and at least 900 seconds after the heat pulse. Install the needles in an asymmetrical geometry around the heater. The typical Compensation Heat Pulse Method (CHPM) configuration is 5mm upstream and 10 mm downstream of the heater. The data can be automatically analysed by importing it directly into Sap Flow Tool software, and applying the CHPM algorithm.

16) How do I check the health of a wet cell external 12 V battery?

Answer: If you suspect the battery is failing to hold a charge or one cell of the battery has gone high resistance, check the health of the battery by measuring the voltage of each cell, if you can, (usually not possible in the field) or check the specific gravity of the cells (again, generally not possible in the field or with gel cell). Alternatively, connect a heavy load, for example, a 12V DC 150W spotlight available from automotive spares stores (such as Supercheap Auto) and see if the battery voltage holds up. Or check the battery voltage at the battery terminals both with the solar panel connected and disconnected (on a sunny day). If the battery is healthy, there should be no more than a 2-3 volt drop (maximum) upon applying a heavy load.

23 Appendices

23.1 Heat Ratio Method Correction Coefficients

Wound (cm)	b	c	d	r^2	B	r^2
A. Standard -0.5, 0, 0.5-cm probe configuration						
0.17	1.6821	-0.0015	0.0002	1.0000	1.7283	0.9993
0.18	1.7304	-0.0013	0.0002	1.0000	1.7853	0.9992
0.19	1.7961	-0.0016	0.0002	1.0000	1.8568	0.9991
0.20	1.8558	-0.0018	0.0003	1.0000	1.9216	0.9990
0.21	1.9181	-0.0021	0.0003	1.0000	1.9891	0.9989
0.22	1.9831	-0.0024	0.0004	1.0000	2.0594	0.9988
0.23	2.0509	-0.0028	0.0004	1.0000	2.1326	0.9987
0.24	2.0973	-0.0030	0.0005	1.0000	2.1825	0.9987
0.26	2.2231	-0.0037	0.0006	1.0000	2.3176	0.9985
0.28	2.3760	-0.0046	0.0008	1.0000	2.4813	0.9983
0.30	2.5232	-0.0055	0.0010	1.0000	2.6383	0.9982
B. -0.6, 0, 0.6 cm probe configuration (non-standard spacing)						
0.17	1.6565	-0.0014	0.0002	1.0000	1.7023	0.9993
0.18	1.7077	-0.0014	0.0002	1.0000	1.7585	0.9992
0.19	1.7701	-0.0017	0.0002	1.0000	1.8265	0.9991
0.20	1.8292	-0.0019	0.0003	1.0000	1.8905	0.9990
0.21	1.8909	-0.0022	0.0003	1.0000	1.9572	0.9989
0.22	1.9554	-0.0025	0.0004	1.0000	2.0267	0.9988
0.23	2.0226	-0.0029	0.0004	1.0000	2.0991	0.9987
0.24	2.0685	-0.0031	0.0005	1.0000	2.1482	0.9987
0.26	2.1932	-0.0038	0.0006	1.0000	2.2817	0.9985
0.28	2.3448	-0.0047	0.0008	1.0000	2.4467	0.9984
0.30	2.4908	-0.0057	0.0010	1.0000	2.5985	0.9983

Table 2. (A) Correction coefficients for numerical solutions derived for a range of wound diameters and corresponding to a –0.5, 0, 0.5 cm probe configuration, where the stainless-steel probes are 1.3mm in diameter. Solutions were derived based on modelled temperature data at t = 60–100 s.

Coefficients b, c and d apply to Equation 6. Coefficient B is a linear approximation (Equation 16) of the polynomial relationship described by Equation 6.

(B) Additional coefficients generated for a –0.6, 0, 0.6 cm probe configuration, with 1.3-mm diameter stainless steel probes.

23.2 Specifications of the SFM1 Sap Flow Meter

MEASUREMENT	
Output Options	Raw Temperatures: °C Heat Pulse Velocity: cm hr^{-1} Sap Velocity: cm hr^{-1} Sap Flow: cm^3 hr^{-1} (Litres hr^{-1})
Range	-100 to +100 cm hr^{-1}
Resolution	0.01 cm hr^{-1}
Accuracy	0.5 cm hr^{-1}
Measurement Duration	120 seconds
Heat Pulse	User Adjustable: 20 Joules (default) approx. Equivalent to a 2.5 second heat pulse duration, auto scaling.
Logging Interval	User Adjustable: Minimum interval, 3 minutes, recommended minimum 10 minutes.
DATA	
Computer Interface	USB, Wireless RF 2.4 GHz
Data Storage	MicroSD Card
Memory Capacity	Up to 16GB, 4GB MicroSD card included.
NEEDLE DESIGN	
Needle Diameter	1.3 mm
Needle Length	35 mm
Measurement Positions	2 per measurement needle
Measurement Spacings	7.5 mm and 22.5 mm from the needle tip
Dimensions L x W X D	170 x 80 x 35 mm
Weight	400 g
POWER	
Internal Battery Specifications	
	960mAh Lithium Polymer, 4.20 Volts fully charged
External Power Requirements	
Bus Power	8-30 Volts DC, non-polarised, current draw is 190mA maximum at 17 volts per logger
USB Power	5 Volts DC
Internal Charge Rate	
Bus Power	60mA – 200mA Variable internal charge rate, maximum charge rate of 200mA active when the external voltage rises above 16 Volts DC
USB Power	100mA fixed charge rate
Internal Power Management	
Fully Charged Battery	4.20 Volts
Low Power Mode	3.60 Volts – Instrument ceases to take measurements
Discharged Battery	2.90 Volts – Instrument automatically switches off at and below this voltage when no external power connected.
Battery Life varies	
	• With a recommended power source connected, operation can be continuous. • Approximately 1.5 days with a heat pulse of 50 Joules and a measurement interval of 30 minutes – no external power present to recharge battery.

23.3 Warranty

The standard Terms & Conditions of the ICT warranty are that the SFM1 Sap Flow Meter is guaranteed to be free of faulty parts and workmanship for a period of 12 months from the receipt of purchase.

The warranty covers back to base repair for faulty parts and labour. The customer is required to pay the cost of shipping to ICT International or an authorised ICT distributor for repair. ICT International will then pay the return shipping costs to the customer upon repair.

SFM1 Sap Flow Meters regularly operate continuously for 2+ years in the field without maintenance and repair. However, as mentioned, heater filaments (as is the case of incandescent light bulbs) have a finite and unpredictable life-span. In this sense, heaters are considered consumables that may require periodic replacement.

On the whole, temperature probes and cables are long lasting if they are well cared for, however no sensor needles (measurement needles or heaters) are immune to the rigours of installation and removal from woody tissue. Accordingly, users are reminded that a degree of attrition is to be expected, and with this in mind, SFM1 Sap Flow Meters are designed so that individual needles can be replaced. The complete SFM1 instrument can be returned to ICT International or a local authorised ICT distributor for repair at a small labour charge plus parts.
In specific terms, ICT International does not guarantee the following:

- Incorrect use or inability to use any supplied equipment.
- Mechanical damage of equipment.
- Heater filament failure (burnout) due to prolonged (> 3 seconds) heating or due to end of natural lifespan beyond the 3-month guarantee period.
- Corrosion or failure of thermocouples within probes or wires within cables due to repeated mechanical stress/natural wear and tear.
- Accuracy of data.
- Correct analysis, interpretation or extrapolation of data.
- Accidental loss of data. Any personal injury or damage to plants, field sites, electronic equipment or any other equipment associated with the use of the SFM1 Sap Flow Meters.

23.4 Equipment

23.4.1 Recommended Equipment

In addition to the SFM1:

- SFM-SK1 – SFM Installation Kit
- SP22 – 22W Solar Panel
- SPPM – Solar Panel Post Mount
- Star Picket
- Figure-8 power cable
- SFM-TB – SFM Test Block
- Cordless Drill (Dremel style recommended)
- Bark Depth Gauge
- Diameter tape (diameter and circumference)
- Coring Tool
- Methyl Orange
- Mounting strap, Velcro, zip ties, nails or screws for fastening the SFM to the plant
- Chisel and hammer for removing bark from the installation site
- Silicone Vacuum grease
- Wire cutters/strippers
- Laptop/Tablet computer with ICT Combined Instrument Software
- Tweezers

23.4.2 Optional Equipment

Optional equipment for installation and data analysis:

- MCC-Mini – USB to ICT Wireless adaptor, for remote data download and instrument configuration
- ICT Telemetry Hub – for data to the web
- Sap Flow Tool Software, for advanced data analysis
- Flat head and Philips screwdrivers
- Tree ID tags

23.4.3 SFM-SK1 Installation Kit

Contains:

Qty	Object	Description	Image
1	Small Drill Guide	Small Drill guide with 5mm spacing. 4 Mounting pins each 8mm long Dimensions: 50 mm x 30 mm x 12 mm	
10	Drill Bits	1.3 mm diameter x 75 mm long drill bits Tolerance ±0.05 mm	
1	Micro-SD card shuttle	The SD Card Reader allows the transfer of data from the SFM1 to a PC, for rapid data transfer of large files	
1	USB – Mini USB cable	Standard USB to Mini USB cable, used to connect the SFM to a computer.	
1	USB Drive	USB Drive containing the SFM Manual, ICT CIS, USB Driver and other support material	

23.5   General Structural Anatomy of a Tree
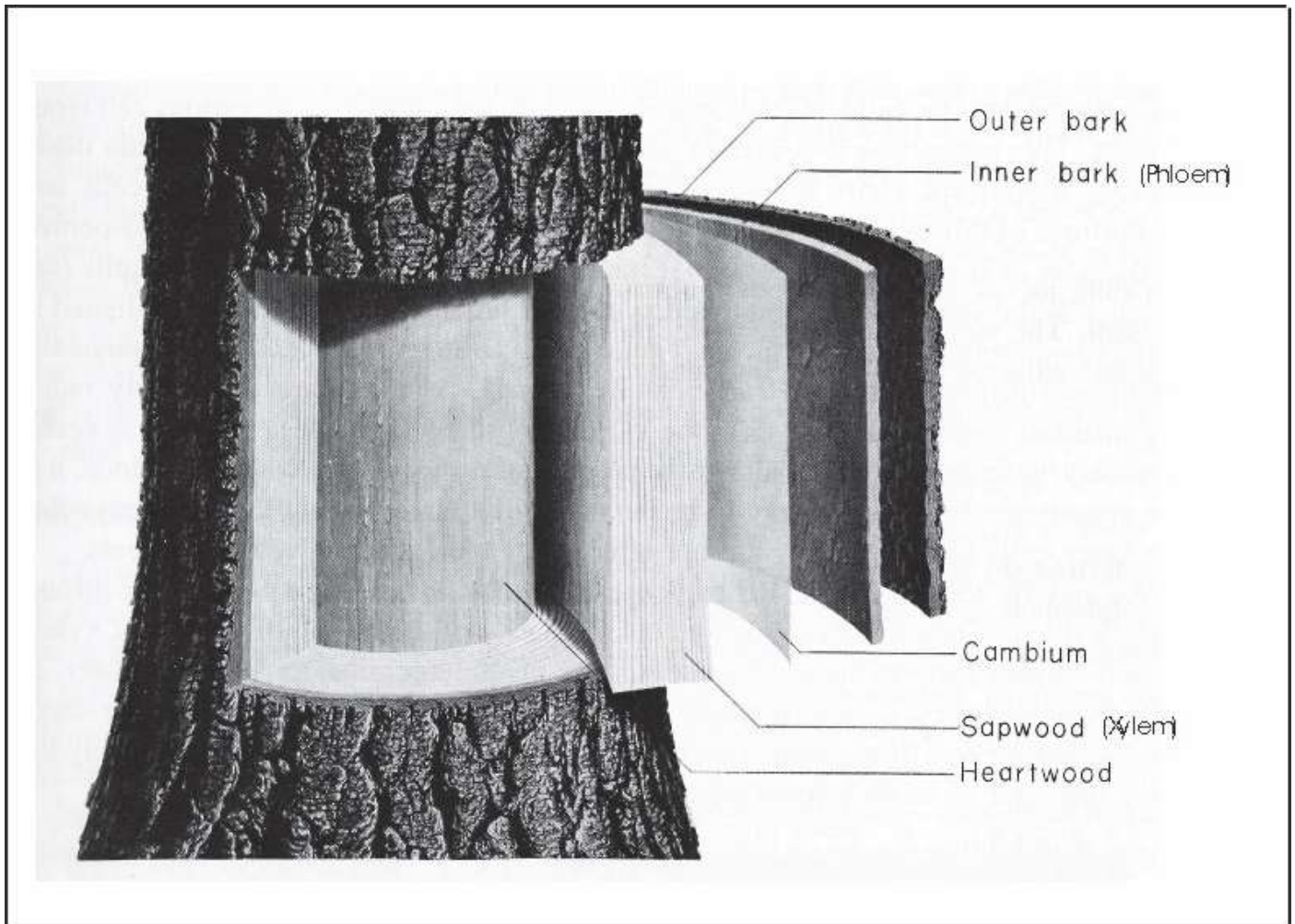
Figure 41: Generalised structure of a tree stem showing orientation of major tissues: outer bark, inner bark (i.e. phloem), cambium, sapwood (i.e. xylem) and heartwood (Kramer & Kozlowski, 1979).

23.6   CIS: Automatic Web Updates

CIS automatically checks for software updates when it is opened. This option can be disabled in the Options dropdown menu.

Updates for software, firmware and drivers are available from:
www.ictinternational.com/support/software/
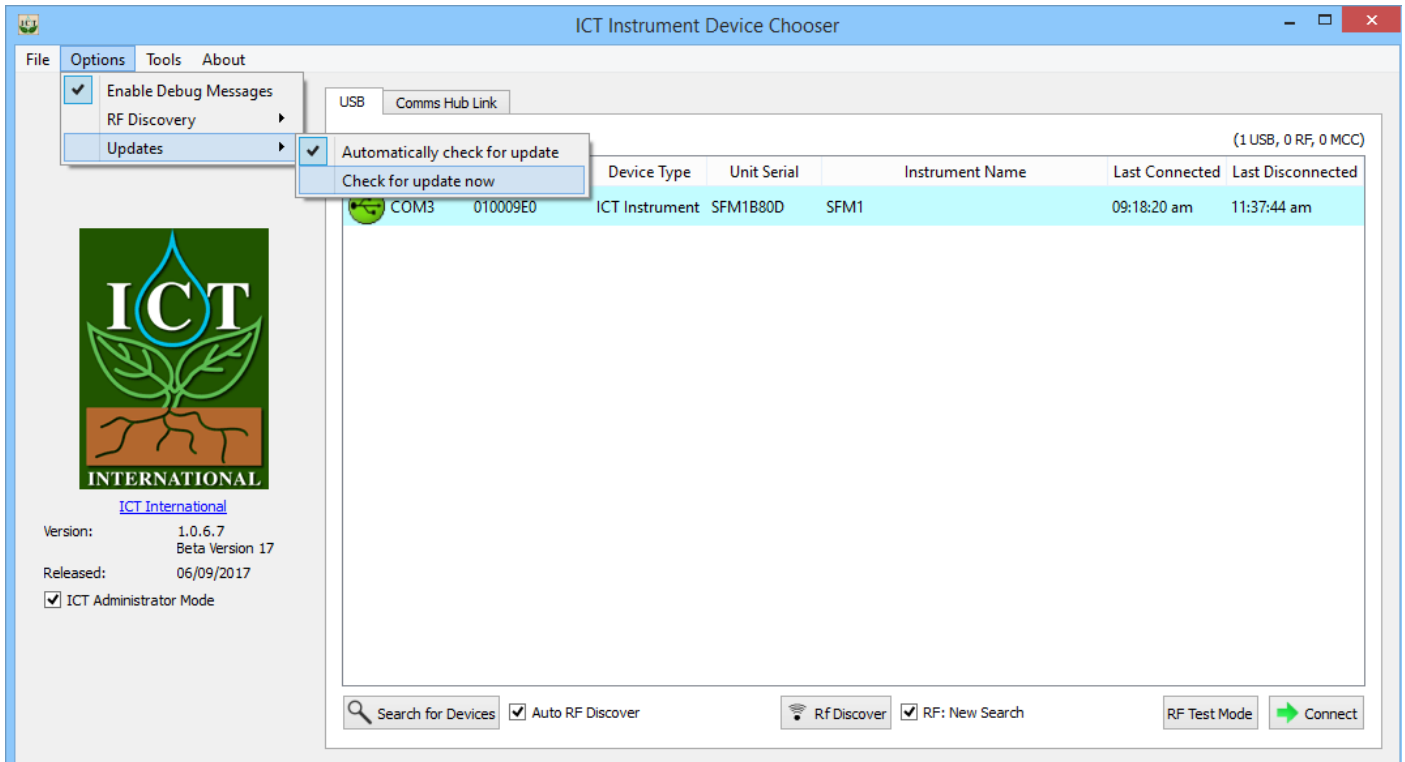
Figure 42: The option to automatically check for updates.

23.7   SFM Test Block

The SFM Test Block is a functional verification standard for use with the SFM1. It is designed using a thermal compound of known thermodynamic properties and encased in a housing of known dimensions. The needle spacings are asymmetrically arranged (which is a divergence from the Heat Ratio principle) to induce an artificial Heat Pulse Velocity. Each block is designed to induce an artificial velocity of approximately 18 cm hr^{-1} or a mid-range value of expected sap velocities as measured by the SFM1 in many species. Depending upon the temperature conditions under which the block is used, the heat dissipation from the block will be higher or lower which will ultimately impact the measured heat ratio causing a small divergence from the expected 18 cm hr^{-1} value. The Test Block is not intended to be used as a calibration device, rather as a known standard for operational verification of the Sap Flow Meter. This can be done in the lab as a pre-deployment check before taking the equipment to the field for installation. This will ensure correct functioning of the two measurement needles and the heater providing confidence in the operation of the equipment and subsequent results obtained, which will aid in data interpretation.

Photo 41: The SFM Test Block.

24   Appendix: Measuring Fresh Weight

Fresh weight should ideally be measured in the field directly upon sampling from the tree. In most cases this is not possible. Therefore, use a Ziploc plastic bag (preferably wrapped in aluminium foil) to seal the sample immediately upon sampling. Place this bag in a stable thermal container such as an ice filled Esky. This will minimise moisture loss, ensuring an accurate measurement of weight when you can weigh the sample.

NOTE 45: If weighing a sap wood core extracted with a conventional forestry coring tool, the weight will be very small. Where possible ensure that any condensation in the bag from the sap wood core is allowed to equilibrate into the sap wood core before removing the core from the plastic bag. If not, weigh the bag, complete with sample, then remove the sample and dry the bag free of any moisture. Finally, reweigh the bag and subtract this weight from the total to obtain the true fresh weight of the sap wood core.

24.1   Measuring Fresh Volume

The fresh volume can be measured in one of two ways.
(1) If the sapwood being sampled has been obtained using a conventional coring tool, the sample will be a symmetrical cylinder (be sure to trim both ends of the sap wood cylinder square). The volume can then be determined by using the formula for the volume of a cylinder:

Volume of a Cylinder
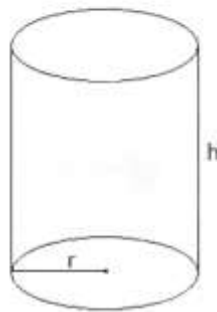
$$V = \pi * r^2 * h$$

Equation 16

Where:
V= Volume
π = Pi (3.14)
r = radius
h = height

(2) In situations with an irregular sap wood sample that is impractical to determine fresh volume using the volume of a cylinder, cube or quadrilateral (Length x Width x height), the volume can be determined using Archimedes' principle of displacement. Which states that:

Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object. - Archimedes of Syracuse

Therefore:

Volume of Object (L) = Weight of Object in Air (kg) – Weight of Object in Water (kg)
Equation 17

or

Volume of Object (cm³) = Weight of Object in Air (g) – Weight of Object in Water (g)
Equation 18

Begin by configuring the sap wood sample to a very thin needle attached to an apparatus that will allow you to submerge the sap wood sample into a container of water.

NOTE 46: Be sure not to submerge the needle as this will add to the measured volume and introduce error to the measurement.

Photo 42: Sap wood sample submerged with a dissection needle on a retort stand, in a beaker of water on a scale.

Place the beaker of water on the scale and zero the scale. Then submerge the sample into the beaker of water. Record the weight on the balance. This will be equivalent to the fresh volume of the sap wood.

NOTE 47: Immediately weigh the fresh weight of the sample after removing it from Ziploc bag. Following the fresh weight measurement submerge the sap wood sample into water and measure the volume displacement. Do not allow the sample to sit between these measurements as the vapour pressure gradient will draw moisture from the sap wood sample and cause error in the measured volume.

24.2 Measuring Dry Weight

Remove the sample from the water after measuring the volume and blot the sample dry. Place it in an oven at 80°C for 48 hours. Check and record the weight of the sample. Return the sample to the oven for another 48 hours, reweigh the sample and record the weight. Continue to repeat this procedure until there is no change in weight of the sample.

NOTE 48: For very small sap wood cores or samples you will require a 4-decimal balance (with a shroud) to accurately measure the fresh weight, fresh volume and dry weight.

Photo 43: A sap wood sample being dried in an oven.

25 Appendix B

25.1 SFM1 External Battery Operation Test (without solar panel)

NOTE 49: The following case study contains out-of-date information and is included purely as an example application. ICT International recommend charging the SFM1 with a solar panel.

NOTE: Continuous connection of an external battery or constant power supply (for days to months at a time) is not recommended as this can shorten the life of the internal battery. ICT International recommend using a solar panel directly connected (with no external battery backup in parallel) wherever possible; or a timer switch to turn off external power for 8-12 hours daily to simulate a solar panel during the day and night.

Aim

To test and determine the longevity of field deployment of the SFM1 Sap Flow Meter using a small 12 V DC, 7 Ah Lead Acid rechargeable battery as the sole source of external power supply to maintain the SFM1 internal 4.2 V, 950 mA Lithium Polymer battery.

As the internal battery has the capacity to sustain the SFM1 for approximately 36 hours, this allows for the ability to either remove a discharged external battery and swap it with a fully charged battery, or remove the discharged battery leaving the instrument to operate independently from the internal battery whilst the external battery is recharged and replaced.

Method

The SFM1 measurement mode was set to a temporal logging interval of 10 minutes, with a Pulse Energy setting of 20 Joules for each heat pulse. The data reporting option was set to Needle Temperature Mode with a sampling frequency of three (3) samples per second and 900 measurements after the heat pulse for each measurement. This results in a total measurement time of 5 minutes and 32 seconds for each measurement of sap flow.

To ensure a thorough test, a new 7.0 Ah Lead Acid rechargeable battery was purchased and placed on charge for the recommended 12 hour period prior to use. This was done to ensure the battery was at full capacity prior to commencing the test. The battery was removed from charge and independently measured with a voltmeter to verify the starting voltage.

The starting voltage immediately measured after removal from charge was 13.67V. This voltage steadily decreased until it stabilised at approximately 13V as measured with the voltmeter prior to connection to the SFM1.

This value of 13V was confirmed by the SFM1 immediately upon connection to the instruments internal power circuit. The voltage of the external 7 Ah battery was measured continuously using the internal voltage monitoring functions of the SFM1 Sap Flow Meter. The data was analysed using the SFT Sap Flow Tool software. The results of the test are displayed below.

Results

The Blue line (as referenced in the legend displayed on the 1st Y-Axis on the left hand side of the graph, Figure 43) is the continuously measured external battery voltage of the 12V 7Ah Lead Acid rechargeable battery. Note prior to commencing the external battery test the SFM1 was connected to a 12V DC mains powered plug pack supplying a relatively constant 13.8V supply.

The external mains power supply was disconnected at (10:50AM 24/10/12) shown by a sudden drop in voltage to zero. The external Lead Acid battery is connected and the first measurement taken at 11:20AM 24/11/12). Note the lower supply voltage delivered by the 12V 7 AH battery (approx. 13V) compared to the mains powered 12V DC Plug pack supplying 13.8V.

The external battery voltage displays a general negative trend as power is supplied to the SFM1. A slight diurnal temperature effect (ambient temperature not specifically monitored although a 25°C diurnal temperature range is common at the site the test was conducted) indicated by minimum battery voltage measured at approx. 5:30AM each morning and a maximum voltage measured at approx. 11:30AM – 12:00PM each day. This correlates (anecdotally) with the maximum and minimum temperatures measured. This fluctuation is most probably due to the ambient heating of the battery resulting in a higher voltage yield or output from the battery as the internal cells are heated.
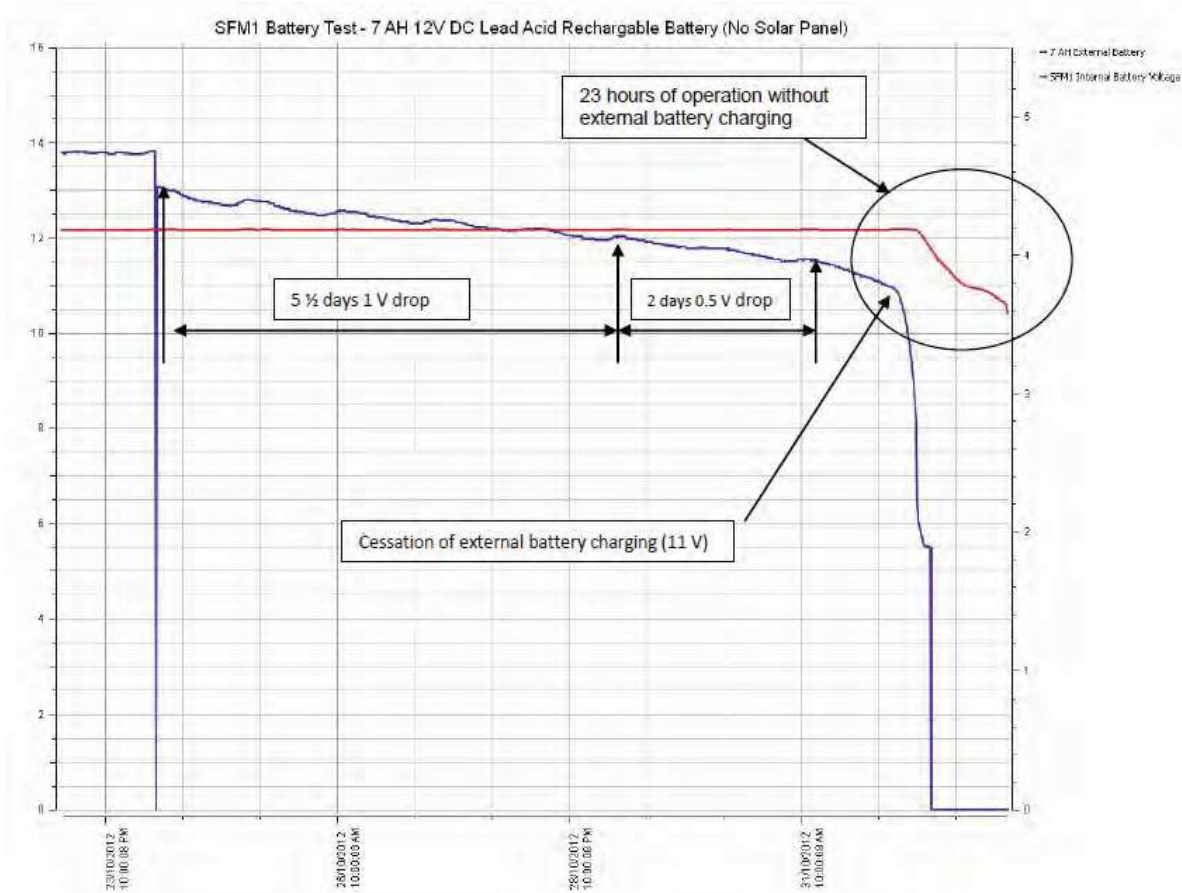
Figure 43: SFM1 Internal battery voltage overlaid against external 7 Ah battery voltage.

The red line (as referenced in the legend and displayed on the 2nd Y-Axis on the right-hand side of Figure 43) is the battery voltage of the SFM1. Note it maintains a constant voltage from before the commencement of the battery test, throughout the external power supply disruption when the external battery was connected (11:20AM 24/11/12) right through in excess of 8 days (4:00PM 1/11/12). At this point the SFM1 internal battery begins to drop as it is no longer being charged.

Conclusions

Based on the results of this test it would appear the SFM1 can be used for independent operation in the field for up to a period of 9 days, 4 hours and 10 minutes using a single (fully charged) 12V DC 7 Ah Lead Acid Rechargeable battery.

As this test takes the external battery to failure (fully discharged) it is advised to reduce the expected longevity for field deployment to 7 days to allow a safety margin to prevent the external battery from being fully discharged. Further testing will be conducted to evaluate the effect of constant deep discharge on the performance of the Lead Acid batteries as it is noted they are not specifically designed for such heavy workloads. Deep Cycle Marine batteries are, however, designed to withstand such heavy workloads and occasional to regular deep

discharge without immediate impact on the serviceable life of the battery. Where possible ICT recommends using large capacity 100 Ah rated (or greater) Deep Cycle Marine grade batteries for charging the SFM1 Sap Flow Meter in field applications when solar charging is not available.

Note: **Continuous connection of an external battery or constant power supply (for days to months at a time) is not recommended as this can shorten the life of the internal battery. ICT International recommend using a solar panel directly connected (with no external battery backup in parallel) wherever possible; or a timer switch to turn off external power for 8-12 hours daily to simulate a solar panel during the day and night.**

26 Glossary

The definitions of these selected terms have been taken from the Penguin Dictionary of Botany 1984, unless otherwise denoted with *

Bark – All the tissues, collectively, lying outside the vascular cambium in the stem and roots of plants showing secondary growth, i.e., the primary and secondary phloem, the cortex, and the periderm. The term is also used in a more restricted sense to mean the tissue arising to the outside of the phellogen, i.e., the phellem, when this is exposed by sloughing off of the epidermis. The bark of different trees can be very distinctive and its characteristics are used to aid identification. In some species, the same phellogen is active each year and a thick layer consisting solely of phellem is formed (e.g. oak, beech), but in most species a new phellogen arises annually in the cortex below: the bark thus consists of both phellem and dead cortex and is termed rhytidome. As the thickness of the bark increases the outer layers may either become fissured (e.g. elm) or be shed as scales (e.g. plane) or rings (e.g. birch).

Cambium – A lateral meristem found in vascular plants that exhibit secondary growth. It gives rise to secondary tissues mostly by periclinical divisions of initial. There are two cambia, the vascular cambium and the phellogen (cork cambium).

* **Corrected sap velocity (Vs)** – Only a portion of xylem tissue (the xylem lumen) contains moving sap. Heat pulse probes effectively measure a weighted average of the velocities of moving sap and stationary wood (Marshall 1958). Sap velocity can be determined by measuring the fractions of sap and wood in xylem and accounting for their differing densities and specific heat capacities.

* **Heat pulse velocity (Vh)** – The velocity at which a known heat input to a plant stem moves a fixed distance between the heat source and two temperature sensors located downstream and upstream from the heat source.

* **Hydraulic lift** – The transfer of water or acropetal (positive) sap flow from great depth in the root zone for redistribution to the shallow lateral surface root system for the supply of water under drought conditions. This has the added benefit of fertilisation of fertigation by remobilisation of minerals and nutrients to the plant.

* **Hydraulic redistribution** – The movement and transfer of water from regions of high water potential to low water potential such as, but not limited to, the transfer of water by roots from moist regions of the soil to a dry region of the soil profile within the plants root zone.

* **Nocturnal Sap Flow** – The acropetal mass flow of solutes within the conducting xylem of a plant after sunset. This movement of water is driven by atmospheric conditions of low Vapour pressure deficit. The term can be used to describe actual night time transpiration where water is lost to the atmosphere though open stomates or hydraulic refilling of the vessels and tracheids of the xylem which may have become dehydrated during the sunlight hours of the day as the xylem supplied transpiration demand from internal storage.

Phloem – (bast) A vascular tissue whose principal function is to translocation of sugars and other nutrients. The phloem is composed mainly of sieve tubes, sclerenchyma cells, and parenchyma cells including; companion cells. It occurs in association with and usually external to the xylem.

* **Reverse flow** – The movement of water or basipetal (negative) sap flow within the tree from the leaves to the roots.

Sap – The liquid, consisting of mineral salts and sugar dissolved in water that is found in xylem and phloem vessels.

* **Sap flow** – The volumetric measurement of acropetal (positive) mass solute flow within a plant stem. It is derived by multiplying the corrected sap velocity (Vs) by the cross-sectional area of the conducting xylem or sapwood of the plant.

Sapwood – (alburnum) The outer functional part of the secondary xylem cylinder as compared to the central non-functional heartwood.

Transpiration – The loss of water by evaporation from a plant surface. Over 90% escapes through open stomata, while about 5% is lost directly from the epidermal cells. It has been shown that although the combined area of stomatal pores is on average only 1-2% of the total leaf area, the amount of transpiration they allow is 90% of the transpiration that occurs from a water surface the same area as the leaf. Transpiration rates are greatest when leaf cells are fully turgid and when the external relative humidity is low. Water forms a film around the mesophyll cells and evaporates into the sub-stomatal chamber from where it diffuses into the air. The degree of opening of the stomata (stomatal resistance) is of prime importance in governing the rate of water loss. The width of the boundary layer at the leaf surface is also important. In dry conditions, transpiration can cause wilting and so the plant may develop features such as waxy cuticles to minimise the problem.

Xylem – (wood) Vascular tissue whose principal function is the upward translocation of water and solutes. It is composed mainly of vessels, tracheids, fibre-tracheids, libriform fibres, and parenchyma cells. It should be noted, however, that all these cell types may not be present in any one wood sample. Wood anatomy is often very important taxonomically, the presence or absence of the various cell types and their distribution within the xylem being important diagnostic characters. The xylem occurs in association with, and usually internal to, the phloem.

26.1   Acronyms

CHPM - Compensation Heat Pulse Method
CSIRO - Commonwealth Scientific and Industrial Research Organisation
DBHOB – Diameter at Breast Height Over Bark
HPV - Heat Pulse Velocity
HRM - Heat Ratio Method
ICRAF - The International Centre for Research in Agroforestry
UWA - The University of Western Australia
SFM – Sap Flow Meter
CIS – ICT Combined Instrument Software
SFT – Sap Flow Tool software

26.2   Algebraic Terms

V_h = Heat pulse velocity
V_c = Corrected heat pulse velocity
V_s = Corrected sap velocity

t_0 = Time to thermal equilibrium of the downstream and upstream probes after release of the heat pulse
t = Measurement time

x_1 = Denotes distance between heater and the downstream temperature needle
x_2 = Denotes distance between heater and the upstream temperature needle
x = The distance (cm) between the heater and either temperature needle

v_1 = The increase in temperature (from initial temperature) at equidistance downstream, x cm from the heater
v_2 = The increase in temperature (from initial temperature) at equidistance upstream, x cm from the heater

a, b, c & d = Correction coefficients for the effect of wounding

k = Thermal diffusivity
K = Thermal conductivity
K_{gw} = Thermal conductivity of green (fresh) wood
K_s = Thermal conductivity of water (5.984×10^{-1} J m^{-1} s^{-1} °C^{-1} @ 20°C)

p_b = Basic density of wood
p = Density of green (fresh) wood (kg m^{-3})
p_s = Density of water = density of sap = 1
F_v = Void fraction of wood

c = Specific heat capacity of green (fresh) wood
c_w = Specific heat capacity of the wood matrix (1200J kg^{-1} °C^{-1} @ 20°C)
c_s = Specific heat capacity of the sap = Specific heat capacity of the water (4182J kg^{-1} °C^{-1} @ 20°C)

m_c = Water content of sapwood

w_f = Fresh weight of the sapwood sample (kg)
w_d = Oven-dried weight of the sapwood sample (kg)

π = Pi (3.142)
C = Circumference of a circle
d = Diameter of a circle

26.3 List of Equations

$$V_h = \frac{x_1 + x_2}{2t_0} 3600$$ Equation 1   p. 22

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) 3600$$ Equation 2   p. 22

$$x_2 = \sqrt{\left(4kt \ln\left(\frac{v_1}{v_2}\right) + x_1^2\right)}$$ Equation 3   p. 24

$$V_h = \frac{4kt \ln\left(\frac{v_1}{v_2}\right) - (x_2^2) + (x_1^2)}{2t(x_1 - x_2)} 3600$$ Equation 4   p. 24

$$V_c = a + bV_h + cV_h^2$$ Equation 5   p. 25

$$V_c = bV_h + cV_h^2 + dV_h^3$$ Equation 6   p. 25

$$V_s = \frac{V_c p_b (c_w + m_c c_s)}{p_s c_s}$$ Equation 7   p. 25

$$V_h = \frac{k}{x} \ln\left(\frac{v_1}{v_2}\right) x3600 \text{ cm h}^{-1}$$ Equation 8 & 9   p. 26 & 57

$$k = \frac{k_{gw}}{pc} 10000$$ Equation 10   p. 60

$$K_{gw} = K_s m_c \frac{p_b}{p_s} + K_w \left(1 - m_c \frac{p_b}{p_s}\right)$$ Equation 11   p. 60

$$K_w = 0.04182(21.0 - 20.0 F_v)$$ Equation 12   p. 60

$$F_v = 1 - \left(\frac{p_b 0.6536 + m_c}{1000}\right)$$ Equation 13   p. 60

$$c = \left(\frac{w_d c_w + c_s (w_f - w_d)}{w_f}\right)$$ Equation 14   p. 60

$$d = C/\pi$$ Equation 15   p. 65

$$V = \pi \times r^2 \times h$$ Equation 16   p. 107

Volume of Object (L) = Weight of Object in Air (kg) – Weight of Object in Water (kg)   Equation 17   p. 108

Volume of Object (cm³) = Weight of Object in Air (g) – Weight of Object in Water (g)   Equation 18   p. 108

26.4   Table of Photos

26.5   Table of Figures

26.6   Table of Warnings

26.7 Table of Notes

Note 1: This manual is best used in conjunction with the instructional videos provided on the ICT International YouTube channel: https://www.youtube.com/c/ICTinternational   P. 7

NOTE 2: ICT Combined Instrument Software requires Microsoft C++ Redistributable 2010. This is available from: https://www.microsoft.com/en-au/download/details.aspx?id=5555   P. 8

NOTE 3: This manual includes hyperlinks to instructional videos to complement each major section for both practical operation and software function. These videos are located on the ICT YouTube channel: https://www.youtube.com/c/ICTinternational.   P. 12

NOTE 4: A unique power-bus plug design was developed by ICT to simplify the electrical wiring process. It minimises the need for custom tools in the field requiring only that the outer cable sheath be stripped back to expose the copper wire.   P. 12

NOTE 5: Additional (more frequent) logging intervals are provided for researchers who wish to specifically investigate the time interval required for heat dissipation in specific species, under specific conditions at different Pulse Energy settings. See Measurement Control for details.   P. 13

NOTE 6: It is important to install the needles in the correct order otherwise the sap flow data will be inverted. This is easily identified from analysis of the data as the data will clearly demonstrate a characteristic diurnal sap flow pattern, however, the values will all be negative. This problem is easily fixed by reinserting the needles in the correctly labelled orientation.   P. 16

NOTE 7: Additional configuration information must be known and entered into the SFM1 Sap Flow Meter in order to accurately measure corrected sap velocity (Vs) and sap flow directly.
See "Corrections" for details   P. 17

NOTE 8: There is no reason to open the enclosure, the USB Port Cap provides access to all necessary interfaces of the instrument such as USB communication port, MicroSD card and power switch.   P. 19

NOTE 9: When updating firmware, be sure that the instrument is charged before attempting the update. Loss of power may cause the firmware to become corrupted. The instrument will not allow a firmware update unless the internal battery voltage of the instrument is above 3.8V.   P. 20

NOTE 10: Whilst the instrument can operate at these extreme temperatures (80°C to -40°C), it is unlikely that the plant will.   P. 20

NOTE 11: The expected heat pulse velocities of the majority of plant species in most environments will be < 60 cm hr^{-1} for conventional (acropetal) flow and no greater than -5 to -10 cm hr^{-1} reverse (basipetal) flow.   P. 21

NOTE 12: ICT recommends the use of 22W solar panels for most applications; or 24V DC mains power supplies for greenhouse/lab applications.   P. 27

NOTE 13: The HRM principle, a ratio method, is not sensitive to the absolute amount of heat released. The measurement is based on the ratio of the temperature rise of each symmetrically placed measurement point in the stem.   P. 27

NOTE 14: All Heat Pulses are generated from the internal battery regardless of any external power source that may be connected.   P. 28

NOTE 15: The SFM1 internal battery provides a unique advantage in that external power supplies can be disconnected and exchanged without losing power to the instrument. This prevents disruption to logging and avoids the need to reconfigure the instrument should it be necessary to adjust or change external power supplies.   P. 28

NOTE 16: ICT does not supply 12V batteries because the shipping & dangerous goods costs to do so are prohibitive. ICT recommends that where multiple SFM1 are daisy chained to a single battery (or battery bank) all batteries used (either wet cell or deep cycle) should have a minimum current rating of 85 Ah. ICT also recommends the use of a battery box. This is a plastic enclosure typically custom moulded to fit a large battery that will protect the battery from environmental elements that will cause a reduced service life and supply problems. Ask your battery supplier for details.   P. 28

NOTE 17: the outer diameter of the insulating sheath of each conductor core of the "figure-8" or "lamp cord" cable should be no greater than 3 mm.   P. 29

NOTE 18: ICT recommends the use of Monocrystalline solar panels as they work better in low-light or shaded conditions. Polycrystalline Photovoltaic cells are less expensive, but have lower efficiency.   P. 36

NOTE 19: Solar Panels should always be pointed North in the Southern Hemisphere or South in the Northern Hemisphere.   P. 38

NOTE 20: The power bus is designed such that water ingress will not damage the instrument or effect instrument operation in any way.   P. 41

NOTE 21: The small protective Bus Plug caps are not used when wires are inserted.   P. 41

NOTE 22: All changes that you make and confirm by clicking the relevant Update icon will be stored in non-volatile memory. That is, they will be retained even if you turn the power off and on.   P. 42

NOTE 23: All software described in the proceeding section is included on the USB drive supplied with the instrument.   P. 42

NOTE 24: The SFM1 can also be charged directly from any computer's USB port, USB charger or power bank.   P. 43

NOTE 25: the USB port cap consists of two parts (a) the large knurled portion and (b) the smaller Gore-Tex vent. You must unscrew the whole port cap by turning the larger knurled portion.   P. 43

NOTE 26: In most cases the user should be able to use their finger to press the button. VERY LITTLE force is required to depress the power button. If you find this technique difficult you can use a small screwdriver or tweezers to gently depress the button.   P. 43

NOTE 27: The SFM1 cannot be turned off whilst connected to external power. Pressing and holding the power switch will just display a Green LED. Using the software will display a warning.   P. 45

NOTE 28: If power is applied to the external inputs during the power down sequence, power down is aborted and the unit will reinitialise.   P. 48

NOTE 29: Where specific targeted artificial stimuli are applied to the plant, in particular, irrigation of a drought affected plant or cutting experiments, a frequency of measurement greater than 10 minutes may be beneficial. For these instances ICT recommends the use of the HFD8 Heat Field Deformation Sap Flow Meter which is a continuously heated technique allowing logging frequencies of every 1 second P. 53

NOTE 30: Sap Flow Mode is generally recommended as it allows for the easiest data manipulation and post processing. Sap Flow Mode records data in csv format, suitable for use with Excel or CIS.   P. 54

NOTE 31: To operate the SFM1 Sap Flow Meter in CHPM mode, the needle spacing must be adjusted from symmetrical spacing 5 mm either side of the heater to asymmetrical spacing 5 upstream and 10 mm downstream of the heater.   P. 54

NOTE 32: For greatest accuracy, synchronise the real-time clocks of all SFM units to your computer's time prior to installation in the field. This can be done by clicking the date and time at the bottom of CIS.   P. 55

NOTE 33: If the temperature rise is less than 0.7°C increase the energy level until the temperature rise is within 0.7°C to 1.5°C. This range ensures good results and will help to eliminate measurement errors. This is especially important during periods of high flow where a lower amount of energy (20 Joules) may be insufficient to generate a measurable temperature rise at the upstream measurement location due to rapid convection of heat away from the thermistor.   P. 56

NOTE 34: Tree size does not affect the Pulse Energy requirements as long as the needles are fully inserted, however wood moisture content and density can.   P. 57

NOTE 35: The default Correction parameters are likely incorrect for any scientific presentation of data. It is important to use the correct values for the plant being measured or to post process the data.   P. 57

NOTE 36: The 6 mm spacing is still relevant and can be used, making a legacy provision for scientists who may already have existing data collected at 6 mm spacings and wish to maintain uniformity of their data.   P. 58

NOTE 37: Whether the offset is a positive or negative adjustment will depend upon the convergence or divergence of each needle relative to the heater. The magnitude of the adjustment can only be assessed after an initial few days of measurements have been analysed. Therefore, this correction parameter must be entered after the first few days of data have been collected.   P. 59

NOTE 38: If entering the correction factors directly to the SFM1 for real-time processing, Thermal Diffusivity should be sampled and determined prior to installation. The process can take up to a week due to the drying time of sap wood.   P. 60

NOTE 39: Due to varying wound response and slight asymmetries caused by the installation procedures, heat ratios vary over time. For this reason, readings are sampled multiple times between 60 seconds and 100 seconds after the heat pulse. This is when the heat ratios are most stable and linear.   P. 61

NOTE 40: The SFM1 should be installed at the same point at which the stem diameter and bark depth are measured.   P. 66

NOTE 41: If it is necessary to remove bark, ensure that a sufficient area is removed to accommodate the drill guide so that it can be placed firmly and squarely to the stem, otherwise it will be difficult to drill the holes parallel.   P. 71

NOTE 42: The drill bits used are made of high speed steel to improve cutting performance and longevity. SFM1-55 drill bits are non-standard specifications, replacement drill bits are readily available from ICT International.   P. 72

NOTE 43: A Dremel cordless power drill is recommended as it has a long-life Lithium Ion battery for long field use and does not have a large, heavy battery located in the handle at right angles to the drill, making it easier to drill parallel holes.   P. 72

NOTE 44: Try to avoid redrilling holes once the drill guide has been removed. The xylem fibres of some species are held under extreme tension and relax after the hole has been drilled, making the insertion of the measurement needle very difficult. In this situation, the hole will need to be reamed out by carefully running the drill back and forth through the hole to cut away the expanded fibres that encroach into the hole. Do not attempt to forcefully redrill the hole. Simply hold the drill without pressure and allow the drill bit to run in and out through the existing hole.   P. 73

NOTE 45: If weighing a sap wood core extracted with a conventional forestry coring tool, the weight will be very small. Where possible ensure that any condensation in the bag from the sap wood core is allowed to equilibrate into the sap wood core before removing the core from the plastic bag. If not, weigh the bag, complete with sample, then remove the sample and dry the bag free of any moisture. Finally, reweigh the bag and subtract this weight from the total to obtain the true fresh weight of the sap wood core.P. 107

NOTE 46: Be sure not to submerge the needle as this will add to the measured volume and introduce error to the measurement.   P. 108

NOTE 47: Immediately weigh the fresh weight of the sample after removing it from Ziploc bag. Following the fresh weight measurement submerge the sap wood sample into water and measure the volume displacement. Do not allow the sample to sit between these measurements as the vapour pressure gradient will draw moisture from the sap wood sample and cause error in the measured volume.   P. 108

NOTE 48: For very small sap wood cores or samples you will require a 4-decimal balance (with a shroud) to accurately measure the fresh weight, fresh volume and dry weight.   P. 108

NOTE 49: The following case study likely contains out-of-date information and is included purely as an example application. ICT International recommend charging the SFM1 with a solar panel.   P. 110

MATERIAL SAFETY DATA SHEET
Methyl orange

STATEMENT OF HAZARDOUS NATURE

Hazardous according to criteria of Worksafe Australia

COMPANY DETAILS

Company:	**ProSciTech**
Address:	PO Box 111, Thuringowa Central Qld. 4817 Australia
Street Address:	1/11 Carlton Street, Kirwan, Qld. 4817 Australia
Telephone Number:	(07) 4773 9444
Fax Number:	(07) 4773 2244

IDENTIFICATION SECTION

Product Name	Methyl orange
Other Names	C.I.#13025, Acid Orange, Dexon, Diazoben, Eniamethyl Orange, Helianthine, Gold Orange, Methyl Orange B, Orange 3, Tropaeol.
Product Code	C118, C1181, C1185
U.N. Number	None allocated
Dangerous Goods Class	None allocated
and Subsidiary Risk	None allocated
Hazchem Code	None allocated
Poison Schedule	None allocated
Use	Biological stain

Physical Description and Properties

Appearance	Odorless orange solid
Boiling Point/Melting Point	>300 deg C
Vapour Pressure	
Specific Gravity	1.00
Flash Point	
Flammability Limits	Not determined
Solubility in water	Soluble in hot water

Other Properties

Ingredients

Chemical Name	CAS Number	Proportion
C.I. Acid Orange 52 (Methyl Orange)	547-58-0	100%

HEALTH HAZARD INFORMATION

Health Effects:

Acute

Swallowed:	Harmful if swallowed. May cause gastrointestinal irritation with nausea, vomiting and diarrhea.
Eye:	May cause eye irritation. This product contains an anionic dye. Similar dyes have not caused injury to the cornea or conjunctiva in documented exposure cases with human or rabbit eyes.
Skin:	May cause skin irritation.
Inhaled:	None allocated
Chronic:	No information found.

First Aid:

Swallowed:	If victim is conscious and alert, give 2-4 cupfuls of milk or water. Never give anything by mouth to an unconscious person. Get medical aid immediately.
Eye:	Flush eyes with plenty of water for at least 15 minutes, occasionally lifting the upper and lower eyelids. Get medical aid
Skin:	Get medical aid if irritation develops or persists. Wash clothing before reuse. Flush skin with plenty of soap and water.
Inhaled:	Remove from exposure to fresh air immediately. If not breathing, give artificial respiration. If breathing is difficult, give oxygen. Get medical aid.
First Aid Facilities:	Eye bath, safety shower
Advice to Doctor	Treat symptomatically and supportively.

PRECAUTIONS FOR USE

Exposure Standards:	No exposure standard established
Engineering Controls:	Use adequate ventilation to keep airborne concentrations low.
Personal Protection:	Wear appropriate protective eyeglasses or chemical safety goggles. Wear appropriate protective gloves and clothing to prevent skin exposure. A respiratory protection program must be followed whenever workplace conditions warrant a respirators use.
Flammability:	Not flammable under conditions of use.

SAFE HANDLING INFORMATION

Storage and Transport:	Wash thoroughly after handling. Remove contaminated clothing and wash before reuse. Use with adequate ventilation. Avoid contact with skin and eyes. Keep container tightly closed. Do not ingest or inhale. Store in a cool, dry, well-ventilated area away from incompatible substances. Keep containers tightly closed.
Spills and Disposal:	Clean up spills immediately, observing precautions. Sweep up or absorb material, then place into a suitable clean, dry, closed container for disposal. Avoid generating dusty conditions. Provide ventilation.
Fire/Explosion Hazard:	As in any fire, wear a self-contained breathing apparatus in pressure-demand, MSHA/NIOSH (approved or equivalent), and full protective gear. During a fire, irritating and highly toxic gases may be generated by thermal decomposition or combustion. Vapours may be heavier than air. They can spread along the ground and collect in low or confined areas.
	Use extinguishing media most appropriate for the surrounding fire. Use water spray, dry chemical, carbon dioxide, or appropriate foam.

OTHER INFORMATION

**Incompatibilities
(Materials to avoid)**

Strong oxidizing agents. Avoid excess heat.

Animal Toxicity Data:

RTECS#:
Cas# 547-58-0:
DB63270000

LD50/LC50:
Cas# 547-58-0:
Oral, rat: LD50 = 60mg/kg

Mutagenicity:
Human mutation data is available. However, methyl orange produced negative and inconclusive results in tests by the EPA Gentox Program.

No other data available.

27   Contact Details

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