EMS 51

SAP FLOW SYSTEM

for large tree trunks

Instruction Manual

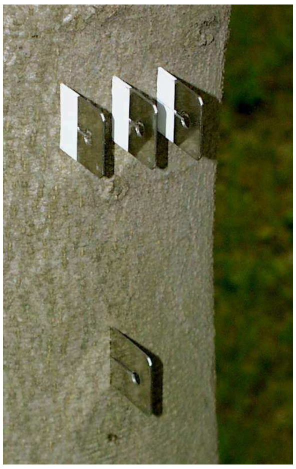
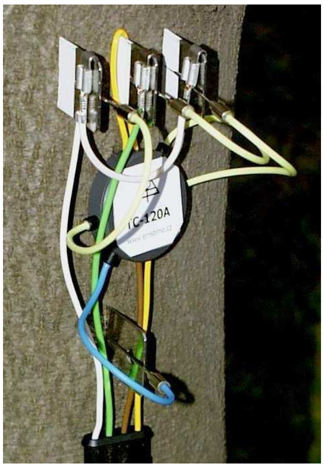
(January 2010)

CONTENT:

1. GENERAL FEATURES

Sap flow module EMS 51 is one-channel battery operated system for the field measurement of sap flow in large trunks with the diameter above 12 cm. The module cooperates with a measuring point composed of a set of four stainless steel electrodes and needle temperature sensors.

The module is designed as a watertight unit containing all electronics necessary for the sap flow measurement based on THB (tissue heat balance) method with internal heating and variable power. The unit supplies xylem tissue around three flat stainless electrodes with an A.C. voltage. The temperature of electrodes is measured with a set of needle thermosensors. The heating power is automatically controlled in order to keep 1 K temperature difference between heated and reference (non-heated) electrodes in the measuring point.


The module is supplied with 11 to 16 V D.C. The power supply current is proportional to the sap flow quantity and it ranges between 40 and 200 mA. Output heating voltage reaches up to 250 Volts according to necessary heating power and the resistance of xylem tissues. Output signal voltage is proportional to the heating power and it can be directly measured or registered by any common datalogger.

The installation of measuring point require special tools for easy hammering of 1 mm thin stainless steel electrodes to exact position against cambium level. Bark and phloem thickness are measured and considered in this operation.

A weather protection set has to cover the measuring point in order to reduce possible errors caused by fast temperature changes, direct solar radiation, wind and rain. Approximately 40 cm of tree trunk is necessary for proper fixing of the weather shield and about 60 cm more for a skirt avoiding irradiation of the trunk below the measuring point.

2. MEASURING PRINCIPLE

The measuring principle is based on the tissue heat balance method (THB) with internal heating and sensing *(Čermák et al. 2004)*.

Three stainless steel plate electrodes are used as terminals leading the A.C. electric current to xylem tissues. The xylem volume around electrodes is heated. The insulated part of electrodes avoids the passing of electric current through high-conductive phloem. Part of the heating energy is dissipated into the ambient by heat conductivity. The rest is carried away by sap flow. Temperature difference is measured between heated and non-heated part of the stem.

2.1. Arrangement of the measuring point

Temperature of the heated tissue is measured in slot at the geometrical center of inserted part of electrodes. The reference temperature related to non-heated part of stem is measured also in the slot at the same type of electrode but installed 100 mm downwards. This arrangement is chosen due to symmetry of the temperature sensing and it is significantly less sensitive to radial temperature gradients caused by daily changes of ambient temperature.

The temperature of heated space along metal electrodes is quite uniform due to their high heat conductivity what makes the measurement nearly independent on the radial sap flow profile. There are three available lengths of electrodes (60, 70 and 80 mm) covering 25, 35 and 45 mm of sapwood depth. Considering the sap flow density decreasing with depth, those electrodes should cover the main part of water conductive profile of most of tree species.

The heat balance of xylem through which the sap flow passes can be described by the general equation:

$$P = Q*dT*c_w + dT*z \qquad [1]$$

where P is the heat input power [W], Q is the sap flow rate [kg/sec], dT is the temperature difference in the measuring point, c_w is the specific heat of water [J/kg, deg] and "z" is the coefficient of heat losses from the measuring point [W/deg]. The amount of water in terms of mass or volume passing through the measuring point in the stem is calculated from the actual power and temperature rise of water passing through the heated space.

The calculation of sap-flow values derives from the equation [1]:

$$Q = \frac{P}{c_W * d * dT} - \frac{z}{c_W} \quad \text{[kg/s, cm]} \qquad [2]$$

The first term of the equation describes heat conducted by sap flow. The second term of this formula represents heat losses from the sensor. Its magnitude can be easily estimated from the data recorded under condition of actual flow approximating zero, i.e., during the zero evaporating demands as during the rain or at night before sunrise. The supporting software Mini32 includes an option for easy graphic baseline subtracting.

Since the measuring point catches just a part of trunk cross section area, the output value has to be written in terms of sap flow per unit of trunk circumference. Because this measuring method in nearly independent on the radial sap velocity profile, the output value is calculated in terms of sap flow per one centimeter of circumference by division with an effective width of heating space ("d"), derived from the horizontal heat field pattern.

3. SYSTEM DESCRIPTION

The measuring system includes the EMS 51 controlling module, thermosensor set TC-120, set of stainless electrodes and connecting cables.

The electronics includes the power unit, the temperature and heating power measuring circuits, the controlling system and the output digital/analog convertor.

Electronic circuits are designed for maximal power efficiency in order to save batteries. Power consumption is directly proportional to heating power.

The sensor protection against the ambient factors is made with a special insulating weather shields. It reflects the sunshine and reduces the effect of the ambient temperature on heat field. It also protects gauges against rain and wind although a little wetness inside does not influence the measurement.

4. SPECIFICATION

Trunk diameter range	12 cm and larger
Heating technique	direct heating of xylem tissues
Output variable	heating power [mW]
Output signal conversion factor	0.8 mW/mV
Temperature sensors	special thermocouple set in 1 mm needles
Xylem resistance span	0.5 to 30 kOhm
Heating power	variable, up to 1.5 W
Frequency of heating current	1 kHz
Power supply	12 – 15 Volts D.C.
Current consumption	Max 0.2 Amp. according to the sap flow magnitude
Working temperature	-10 to 40 Deg.C
Weight	ca 0.5kg (module)
Box size	160 x 80 x 60 mm

5. OPERATION

Measuring system consists from the measuring sensors and module. The measuring module is hanged directly below the measuring point and connected to battery and datalogger by cable. The measuring point is protected against ambient factors by a "hat" made from a foamed polyethylene covered by reflective foil on the surface. The module hangs down just bellow the hat and it is protected together with tree trunk against direct sunshine with a "skirt" made from similar material.

5.1. Sensor installation

Correct installation of measuring points on trees is an ultimate pre-requisite of getting correct results. Interactions between sensors and living tissues belong to important points of this type of measurement.

5.1.1. Sensor location on tree trunks

Fundamental criteria for location of measuring points at tree trunks are the homogeneity of tissue and height above ground. The highest temperature gradient, which may interfere with the measurement, appears close to ground surface. Therefore, measuring points should be placed at least at the height 1 m above ground or higher but below green crown (first living whorl). Trunk tissues should be homogenous enough, i.e., with no irregularities such as knobs, mechanical or biotic injuries, or anything else what could influence the ordinary xylem water flow pathways around the trunk. All possible circumstances should be considered at this point. Take into account the necessary space around the measuring point where the weather shield should be fastened.

In order to reduce the influence of natural variability of sap flow along the circumference of large or irregular tree trunks, two measuring points on opposite sides of tree trunks could be installed. This might be also useful in stands with variable soil conditions, in trees growing on slopes, etc. The whole tree value is calculated as an average from sap flow values measured on both sides.

5.1.2. Sensor set up

In order to measure the position of sensors at tree trunks properly it is necessary to have a certain standard level or surface (i.e. uniform bark thickness). Smooth bark surface in some species is suitable for this purpose, but usually it is necessary to smooth the bark artificially. Bark thickness above the cambium layer should reach about 4-15 mm. This may be done with a sharp drawknife. Attention must be paid to prevent any damage to living tissues below the cork layer of bark.

When two measuring points on the opposite sides of tree trunk are proposed, their vertical level should be either nearly the same (large trunks) or different for more than 30 cm (especially for thin trunks). It avoids the warming of reference electrode from the opposite measuring point and also allows setting up the weather shield.

The sensor installation requires a special tool in order to insert the electrodes to exact position. The installation process takes following steps:

- bark and phloem thickness measurement
- inserting of electrodes
- placing of thermosensors to slots in electrodes
- connecting heating terminals to electrodes
- cable connection
- fixing of the weather shield

See installation guide.

The proper length of electrodes should in principle cover the most of water conductive profile. The available electrode types (60, 70 an 80 mm) cover 25, 35 and 45 mm of sapwood depth. Therefore, general knowledge of the sapwood size and properties is necessary. On the other hand, the principle of the method is not too sensitive to the sapwood thickness and a bit longer electrodes are generally better that the short ones.

Weather shield protects the measuring point and the stem below against the direct sunshine and partially against rain. Thorough protection of the measuring point against stem flow is not necessary since the wet bark surface below the shield does not influence the measuring process.

5.2. Module set-up

The module runs immediately after connecting to power. **Note that the high voltage can appear on the heating terminals. Never run a module not properly connected to electrodes!** The operation after the system was set up does not require any human intervention. Operation status is indicated on the display where all relevant values are shown – heating power [mW], temperature difference [K], el. resistance between electrodes and the power supply voltage. Note that the system is automatically switched off when the power voltage drops bellow 10.5 V. The necessary voltage for restart is 12.1 V in order to avoid on/off oscillations under flat battery status.

5.2.1. Error messages

In case of some troubles, the module displays most of possible errors. It can indicate:

- broken thermosensors (*Thermosensor malfunction!*)
- disconnected electrodes (*Open circuit!*)
- insufficient power when the power unit cannot follow an extremely high sap flow magnitude (*Sapflow too high!*)
- resistance and sap flow rate combination out of operation limit (*R or Q too high!*)
- too low (rotten tissues) or too high (xylem dried up) resistance between electrodes (*Resist. too low!*, *Resist. too high!*)

- switching off the power due to more than ten minutes of maximal heating (risk of overheating due to a feedback malfunction) (*Temporarily Off*). The system is automatically switched on again after two hours.

These messages help to find the problem in the measuring point including the module itself. Read first the module display before any troubleshooting.

5.3. Sap flow calculation

Sap flow values in terms of [kg/h, cm] are calculated from the output signal [mV] according to the formula

$$Q = 0.000125 * U_{sig} \qquad [3]$$

The formula is derived from equation [2] with respect to module output signal conversion factor. The effective width is set to 5.5 cm *(Kucera, unpublished data)*.

Note that sap flow values calculated in this manner include the power loss from the measuring point that has to be (graphically) subtracted!

Derivation details:

$$Q[kg/h,cm] = \frac{P[W]*3600}{c_w[J/K,kg]*d[cm]*dT[K]} - Q_{idle}[kg/h,cm]$$

The calculated sap flow rate is in terms of sap flow per one centimeter of circumference at the cambium level. The whole tree calculation needs the knowledge of circumference at this level. See bellow.

The value "3600" converts the sap flow values to kilograms per hour from kilograms per second (note that "J" = "W.sec"). The following equation considers constant dT (1 K), effective width (5.5 cm) and module conversion factor (0.8 mW/mV) :

$$Q[kg/h,cm] = \frac{U_{sig}[mV]*0.8*3600}{41868[J/K,kg]*5.5[cm]*1[K]} - Q_{idle}[kg/h,cm]$$

and after calculation

$$Q[kg/h,cm] = 0.000125 * U_{sig}[mV] - Q_{idle}[kg,h,cm]$$

5.4. Data handling – EMS dataloggers

When an EMS datalogger is used for data collecting, the equation for sap flow values calculation is already included in the sensor library. **Please refer also to Mini32 software manual for more information.**

5.4.1. Sap flow values calculation

When the *F063* equation (Sap flow EMS51) is chosen for the sensor library, the sap flow values in terms of [kg/hr] are calculated from the module output [mV] according to equation (4) automatically during the conversion from downloaded *.hex file to *.dcv file format suitable for next operation.

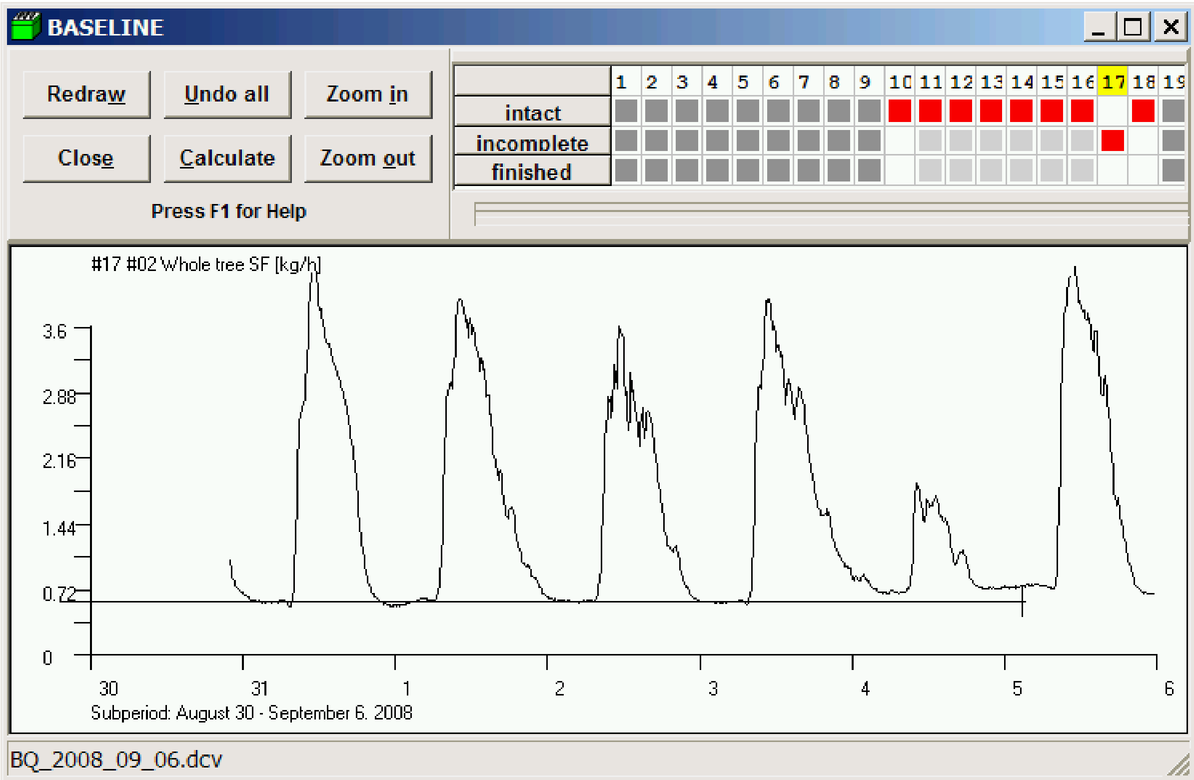
By default channel setting the sap flow rate per unit of trunk circumference is calculated [kg/hr, cm^{-1}]. The parameter A is set to one, the B to zero. When the A parameter is set to stem circumference (with bark) [cm] and B to bark+phloem thickness [cm], the sap flow value extrapolated to the whole stem is calculated according to formula:

$$Q_{tree} = Q*(A - 6.28*B) \quad \text{[kg/hr]} \qquad [4]$$

The obtained values still includes heat lost in space by the diffusion. In order to get "net" sap flow data, it is necessary to subtract (manually) the baseline representing the "fictitious flow" due to heat loses from the heated space. See next paragraph.

5.4.2. Baseline subtraction

The Mini32 software is ready for graphic subtracting of the "baseline" that represents the heat losses from the measuring point (see Eq. [2]). This option automatically appears when the software recognizes a data file coming from a sap flow system. While working with files coming from some older loggers is necessary to press Alt+F8 keys in graphic setup screen in order to activate the baseline button.



Note: Colors in upper line indicate channel status from the point of view of sap flow measurement:

- *black – unused channels (no one in following picture)*
- *grey – voltage channels generally suitable for sap flow measurement but when no sap flow gauges from gauge library were selected (a special case when a general polynomial equation has been chosen instead of predefined sap flow gauge)*
- *red - predefined sap flow channel (EMS51, EMS52, THB 4 el; 0.63 etc.)*

Daily courses of sap-flow values from a chosen channel are displayed on the screen. The keyboard arrow keys driven cursor that appears on the beginning of x-axis allows creating a line connecting the points on the curve that shows the situation at 3 a.m. - zero line. This way, the “fictive” sap flow values caused by heat losses from the sensor are subtracted. The filename with character "&" at the end is offered and this is the file with the correct sap flow values expressed in [kg/hour].

When creating the zero-line, it is necessary to consider the possibility of the night flow during warm summer nights, changes of heat losses as a consequence of changes of sapwood water content, etc. Zooming x-axis to longer time interval sometimes helps to see the trend. Specialist's experience on the field of plant water relations is very valuable since a significant error in zero line setting could be crucial under low sap flow rates.

5.5. Switching off

Disconnect the 7-pin connector leading to the datalogger and power supply from the module box.

5.6. Sensor dismounting

Sequence of dismounting operations:

- Remove the weather shields.
- Disconnect the cable connectors.
- Unplug the module from the measuring point set.
- Remove the terminals from electrodes.
- Remove the thermosensors needles - use a special tool at any case. Do not break connecting hoses with tiny wires inside!
- Remove the electrodes with the special tool.
- Fill the gaps after electrodes with a natural wax.

5.7. Maintenance

Principally, the sap flow rate measuring equipment does not need any special maintenance. Clean up the electrodes and thermosensors after sensor dismounting. Use a mixture of spirit and light petrol. Do not immerse thermosensors to this solution for longer than a few minutes otherwise hoses get hard.

6. WARRANTY

The producer warrants right function of the sap flow rate measuring device for three years after it is accepted by a customer. All the faults will be removed free of charge during this time, at the measuring device itself as well as at sensors. The producer is not responsible for the faults originated by careless manipulation, incorrect operations, wrong applications or theft.

Literature:

Tatarinov, F., Kucera, J. and Cienciala, E. (2004) The analysis of physical background of tree sap flow measurement based on thermal methods. Meas. Sci. Technol. 16 (2005) 1157–1169.

Cermak, J., Kucera J., Nadezhdina, N. (2004) Sap flow measurements with some thermodynamic methods, flow integration within trees and scaling up from sample trees to entire forest stands. Trees 18: 529-546.