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Sap flow system EMS 81

composed of

Sap Flow module SF 8X (SDI-12)

and

Sap flow sensor SF 81

and (optionally)

Stem Increment sensor DR26E

User's manual – 2-nd issue

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Content:

1. Introduction

EMS 81 is the most recent version of sap flow system based on a tissue heat balance (HB) method. Since 1973 when it was established, the instrumentation was seriously upgraded and theoretical background was developed and verified.

The biggest advantage of this approach is direct heating of relatively large volume of xylem which brings high accuracy of the sap flow estimation.

The technology is relatively energy demanding (but comparable to other sap flow systems), the measuring unit is quite sophisticated and therefore also expensive but the underlying theory is clear, without any uncertain empirical parameters (*Tatarinov et al. 2005*) and without any need for field calibration.

Latest system EMS 81 enables connection of the sensor for continuous measurement of stem increment. This additional device synergistically increases the value of measured data (i.e. indirect estimation of the stem water potential, calculation of water use efficiency).

2. General features

Measuring sensor consists of the SF 8X (SDI-12) module designed for connection to **SDI-12** network, sap flow sensor SF 81, set of stainless electrodes, weather shields and connecting cables.

SF 8X module contains the advanced electronics intended for measurement of sap flow rate using the HB method. Its hardware can support various sensors for sap flow measurements, depending i.e. on the size of the stem or branch. SF 8X maintains set temperature difference between measuring and reference part of the sensor which is done by varying the heating power. The electronics is designed for maximal energy efficiency and flexibility in terms of connected HB sensors. The sap flow values in [kg h^{-1}] are calculated directly according to the sensor parameters in EMS Mini32 software.

The unit has an additional input intended for stem increment sensors with potentiometric transducer (i.e. DR26).

Note: The electronics of the unit is quite complex due to following reasons:

- *It must supply heated xylem with alternating current in order to avoid electrochemical processes in the xylem tissues*

- *It must keep preset temperature difference between heated and reference parts of the measuring point (computed as the average value from three points) with accuracy better that 1 %.*
- *It must calculate exact effective value of power of non-sinusoidal power voltage*
- *It has to supply the load with the resistance between 200 to 25,000 ohms with the power ranging between 0.1 to 5 Watts*
- *It has to keep the overall efficiency of the electronics above 80 % in the whole range of operation.*

Sap flow sensor SF 81 is intended for installation in tree trunks larger than 12 cm. Inserted to slots in stainless electrodes it assures that sap flow values are nearly independent on the radial profile of sap flow density.

Stem increment sensor DR26E

DR 26E is designed for long-term measurement of tree trunk circumference by stainless tape that encircles the tree trunk. Its length variations are measured with a rotary position sensor. The sensor output fits to direct connection to sap flow module. Refer to DR26 sensor user's manual for installation details.

3. Measuring principle

The measuring principle is based on the HB method with internal heating and sensing *(Kučera et al.1977, Čermák et al. 2004)*.

Three stainless steel plate electrodes are used as terminals leading A.C. electric current to xylem. The xylem volume around electrodes is heated by flow of electric current among the electrodes. Insulated part of electrodes avoids passing of electric current through high-conductive phloem. Part of the heating energy is dissipated into the surroundings by heat conductivity of the xylem tissue while the rest is carried away by sap flow. Calculation of sap flow is based on the amount of heat carried away by the sap flow, which is computed from the power needed to maintain preset temperature difference between heated and non-heated part of the stem.

3.1. System description

Measuring system consists of the SF 8X controlling unit, sap flow sensor SF 81, set of stainless electrodes, weather shields and connecting cables.

The measuring point at the tree is protected against ambient factors, mainly against direct sun irradiation, by means of reflective insulating weather shields. It reflects the sunshine and reduces the effect of the ambient temperature on the heat field. It also protects sensor against heavy rain and wind although a little wetness on the stem does not affect measurements.

The stainless electrodes (terminals) are hammered into the stem using special tools. The electrodes have to be inserted in parallel, according to installation manual. It is highly recommended to follow instruction for installation since even apparent details might be crucial for the accuracy of the measurement.

Thermosensor needles are inserted into the geometrical center of that part of electrode inside xylem. Highly conductive steel equalizes radial differences in temperature of the sapwood and allows measurement of mean xylem temperature.

Electronic unit controlling the measurement, SF 8X, is attached to the sap flow sensor SF 81 and is hanging below the measuring point.

The address of the unit is available from outside after approaching a magnet of the module. Number of short beep indicates one units, longer beep five units. The sum of units gives the ordinal number of the address. If there is a problem with the sensor operation, the error status is indicated by number of short beeps following a short jingle.

The unit is well protected against reverse polarity of powering and overvoltage (by solar powering, the voltage can reach up to 25 V when the battery is disconnected).

The sensors are interconnected in the SDI-12 network by means of 3-wire cables equipped with 'Superseal' connectors of different gender on their ends. Neighboring units are connected by standard 12 m or 8 m long cables in a chain. Cables are connected to modules via special splitters containing two Superseal connectors of different gender.

3.2. Arrangement of the measuring point

Temperature of heated xylem is measured by needle sensors inserted in slots to the geometrical center of active part of electrodes. Reference temperature related to non-heated part of stem is measured also in the slot in the same type of electrode installed 100 mm downwards. This arrangement provides thermal symmetry of the temperature sensing; it is significantly less sensitive to radial temperature gradients caused by daily changes of ambient temperature.

Temperature of a 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 main part of water conductive profile of most of tree species.

3.3. Sap flow calculation

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

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

where P is power of heat input [W], Q is sap flow rate [kg s^{-1}], dT is temperature difference within the measuring point, c_w is specific heat of water [J kg^{-1} K^{-1}] and z is coefficient of heat losses from the measuring point [W K^{-1}]. Amount of water in terms of mass or volume passing through the measuring point in a stem is calculated from the power input and temperature rise of water passing through the heated space.

Calculation of sap flow derives from the equation [1]:

$$Q = \frac{P}{c_W * d * dT} - \frac{z}{c_W} \quad [\mathrm{kg\ s^{-1}\ cm^{-1}}] \qquad [2]$$

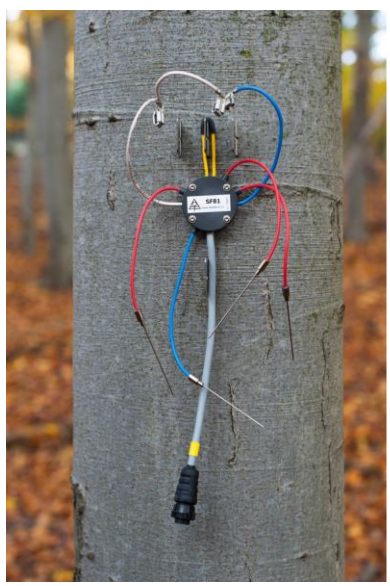
Where d is effective width of measuring point (5.5 cm). First term of this equation quantifies amount of heat that is lead away by sap flow. Second term represents heat loss from the sensor. This loss can be estimated when sap flow approaches zero, i.e., during the rain or at night before sunrise. Supporting software Mini32 includes an option for easy graphic subtracting of heat loss (baseline subtracting).

Since the measuring point captures just a part of trunk cross section area, the output value has to be 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 stem circumference. Whole tree sap flow is then calculated by multiplying the unit sap flow by stem circumference at cambium.

4. Operation

4.1. Sensor location on tree trunk

Sap flow sensors SF 81 may be installed on trunks with diameter larger than 12 cm. Fundamental criteria for location of measuring points on tree trunk are the homogeneity of tissue and height above ground. Highest temperature gradient which may interfere with the measurement occurs close to ground surface. Therefore, measuring points should be placed at least at the height 1 m above ground but still below the living crown and well shielded against weather. Stem tissues in the place of future measuring point should be homogeneous enough, i.e., with no irregularities such as knobs, mechanical or biotic injuries, or anything else that may affect normal xylem water flow. 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 complex soil conditions, in trees growing on slopes, etc. The whole tree sap flow is calculated as an average from sap flow values measured on both sides. However, with respect to often limited budget, sap flow is usually measured only from one side of the trunk. Only when there are reasonable doubts about the regularity of sap flow along the stem circumference, two measuring points on one tree might be installed.

4.2. Sensor installation

In order to set up the measuring point at tree trunk properly it is necessary to have a certain standard level of surface (i.e. uniform bark thickness). Smooth bark surface of some species is convenient but sometimes is necessary to smooth the bark artificially. This may be done with a sharp drawknife. The bark and phloem thickness has to be less than 15 mm above the cambium. 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 installed, they should be either in the same height (large trunks) or vertically separated by more than 30 cm (especially for thin trunks) to avoid warming of reference electrode from the opposite measuring point and also to allow setting up the weather shield.

The sensor installation requires special tools in order to hammer electrodes properly:

The installation process consists of following steps:

- bark and phloem thickness measurement
- hammering of electrodes
- cleaning slots in electrodes with a special rasp
- hanging sap flow sensor SF 81 on the central electrode
- inserting of thermosensors into slots in the electrodes
- connecting heating terminals to the electrodes
- connection of SF 8X unit to the sensor
- connection of SF 8X unit to SDI-12 network
- covering of the sensor by the weather shield

Note 1: It is good idea to run the measurement before installation of weather shield. In case of problem one can easy check the installation.

Note 2: When connecting the sensor to the unit it makes sometimes problems to find right position of both parts. Here are matting instructions of manufacturer:

First, align the notched keyway on both the panel mount and cord connector. Then, push the cord connector onto the mating connector. Grasp the coupling ring between the slots, push it toward the panel mount connector and rotate it clockwise nearly one half a turn. Continue rotating until you feel the coupling ring ride over the locking "bump". This is the locked position. The cord connector is not securely in place unless this procedure is followed.

The electrodes of proper length should in principle cover 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 method is not too sensitive to the estimation of sapwood depth and bit longer electrodes are generally better that short ones. Weather shield protects the measuring point and the stem below it against direct sunshine and partially against rain.

The hammering of electrodes may seem as a horrible attack on tree tissues. In reality, sliding of thin stainless plates to the xylem is less disturbing that drilling holes that leaves saw dust inside the stem disrupt vessels above and below the hole and leads to cavitation of vessels around the hole.

Correct installation of measuring points on trees is an ultimate prerequisite of getting correct results. Interaction between sensors and living tissues belongs to important points of this type of measurement. From this point of view each type of HB sensor is a compromise between accuracy and interference with living organism. The more elements are installed into the tissues, the more is affected the water-conductive system at least in terms of water pathways and water potential.

See installation guide for description of the whole procedure.

4.3. Datalogger operation

For those using EMS technology please refer to EMS datalogger manuals: GreyBox N2N, RailBox or MicroLog MP SDI. Those users can also use the support of Mini32 software for extremely efficient data processing.

4.4. Data handling (for Mini32 users)

Operations with data are supported by Mini32 software. The software offers many features from data downloading, chaining files downloaded during the season into one longer file, mixing files containing data from other trees or from other measuring systems (meteorological data, soil water data) up to advanced processing (non-linear multi-regression analysis, user programming calculation etc.). Big advantage of Mini32 software is fast viewing and processing of long time series with respect to details. See 'Mini32_intro.pdf' and 'Mini32_users_manual.pdf' documents for more information.

4.4.1. Sap flow values calculation

Sap flow values are calculated according to equation (2) automatically during the conversion from downloaded HEX file to DCV file format which allows further operation.

According to datalogger configuration the value of sap flow rate can be calculated in terms of the sap flow per 1 cm of stem circumference [kg h^{-1} cm^{-1}] or per whole tree [kg h^{-1}] according to formula:

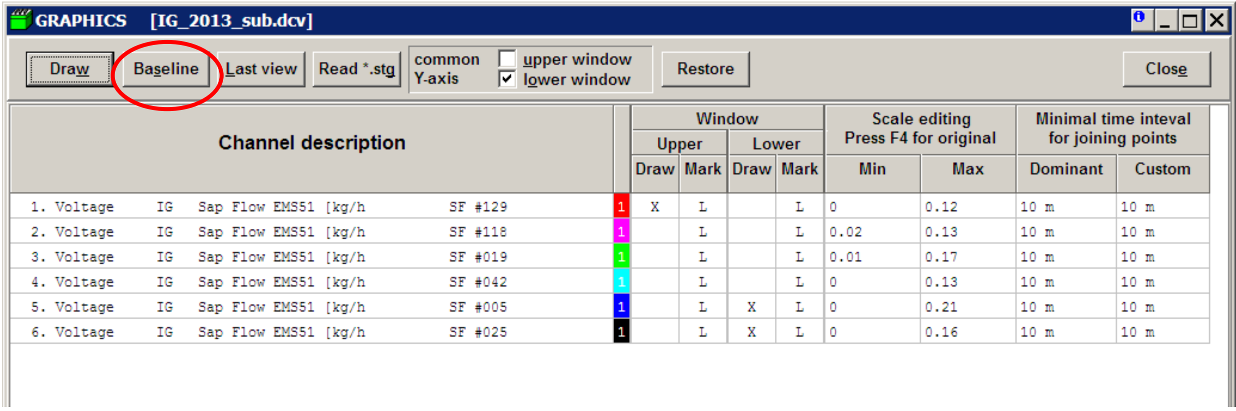
$$Q_{tree} = Q*(A - 6.28*B) \quad [\text{kg h}^{-1}] \qquad [3]$$

Where A is tree circumference in [cm] and B is the thickness of bark and phloem [cm].

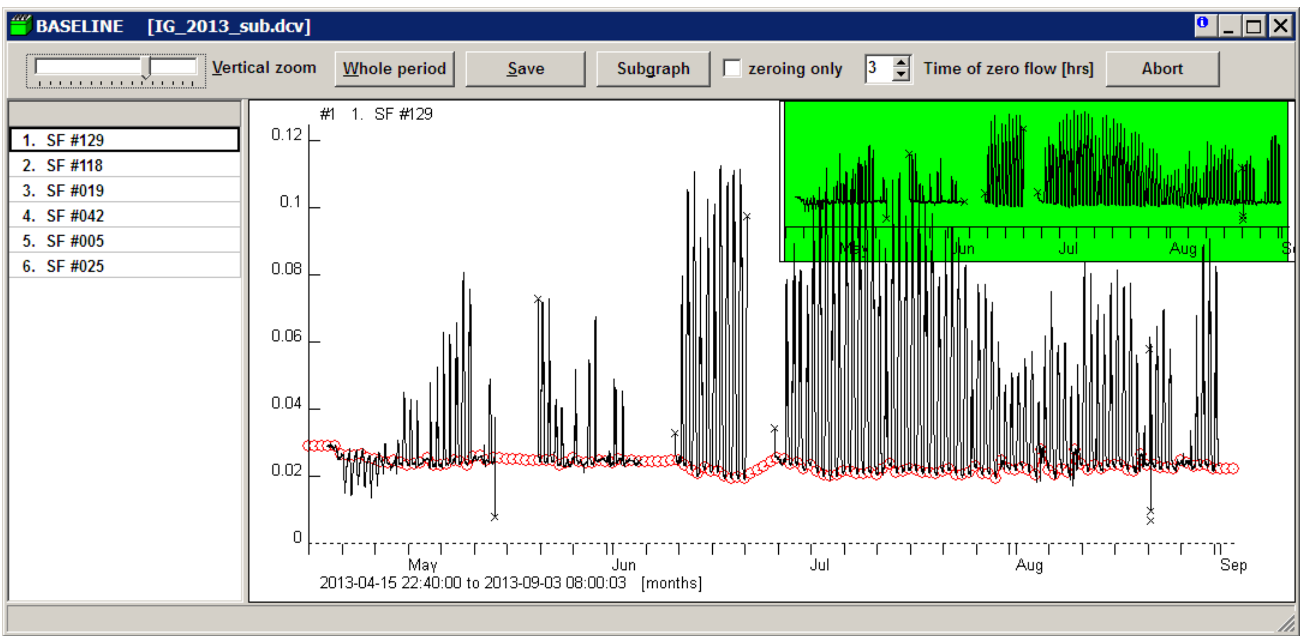
4.4.2. Baseline subtraction

Calculated values still include that part which represents heat loss by heat conductivity of xylem. In order to get 'net' sap flow data, it is necessary to manually subtract baseline representing the 'fictitious flow' due to heat loss from the heated space.

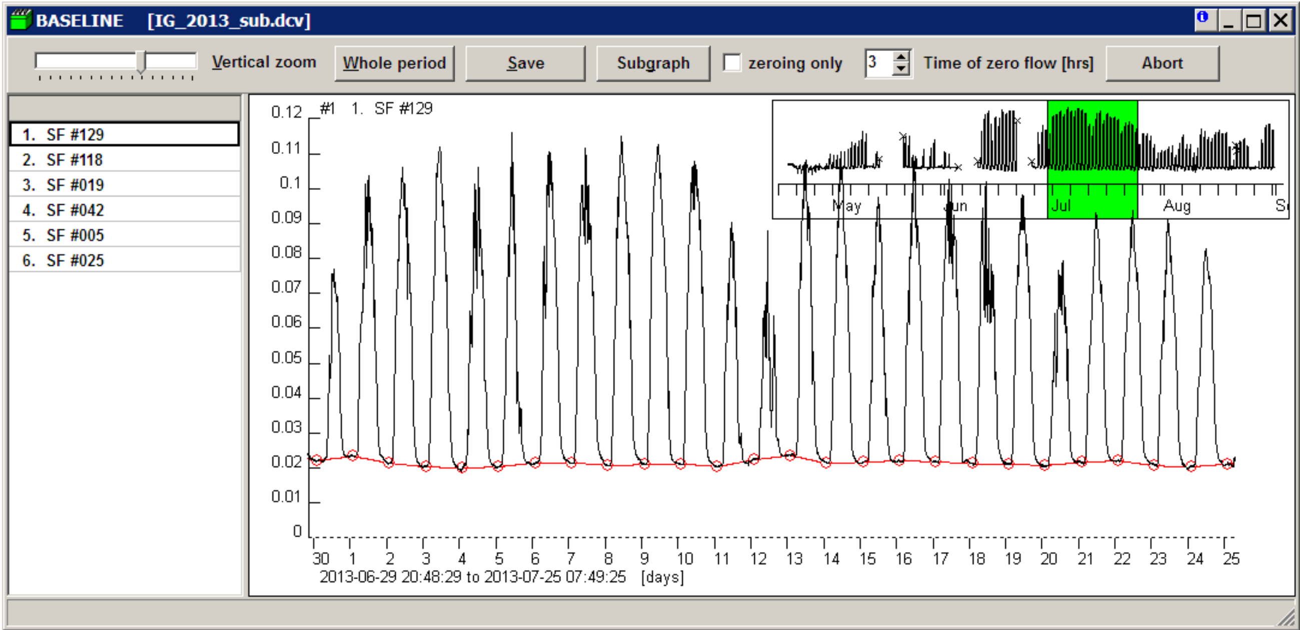
Mini32 software is ready for graphic subtracting of the 'baseline' that represents heat losses from the measuring point (see Eq. [2]). This option is offered in the graphic setup screen:



When entering the 'Baseline' option another graph showing measured variables is displayed:

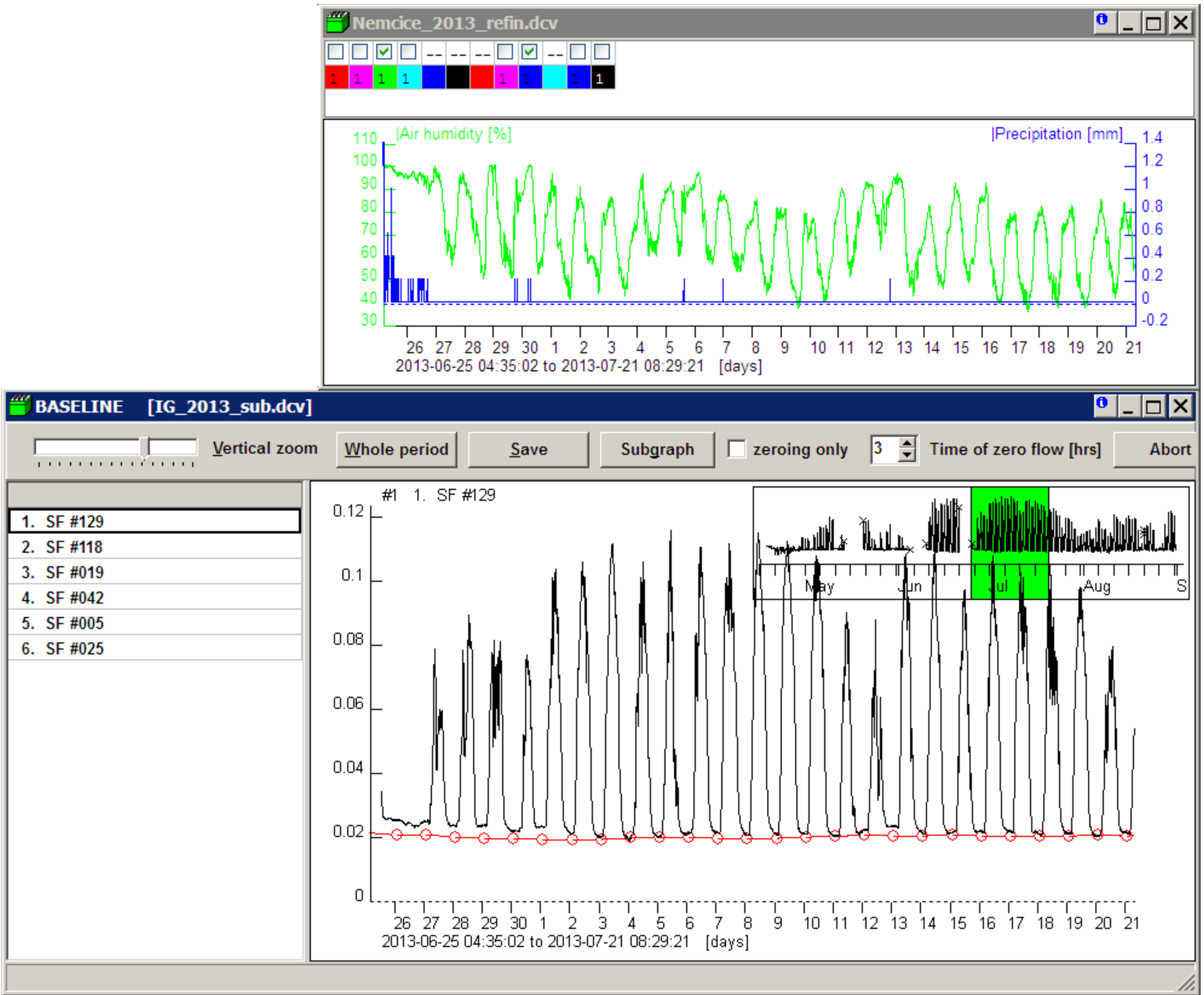


The part in a green window shows whole time period for the case of zooming of a main graph:



The red line with circles is created automatically – it connects values at 3 a.m. when the lowest or zero sap flow is expected (this time point can be changed if necessary in the gray window above the graph). The task of baseline subtracting is to adjust this line the way which should represent the heat loss. This part of data processing requires user's cooperation. In some cases, sap flow can be considerably high even in the night (i.e. when there is still a significant vapor pressure deficit or the sap flow continues because of low tree water potential due to insufficient soil water supply). Then user has to move red circles in vertical direction in order to create the line in terms of sap flow which will be subtracted from recorded values. If more information is needed (for example about vapor pressure deficit), another graph with relevant meteorological data can be displayed; the values can come either from the same or from different file ('Subgraph'):

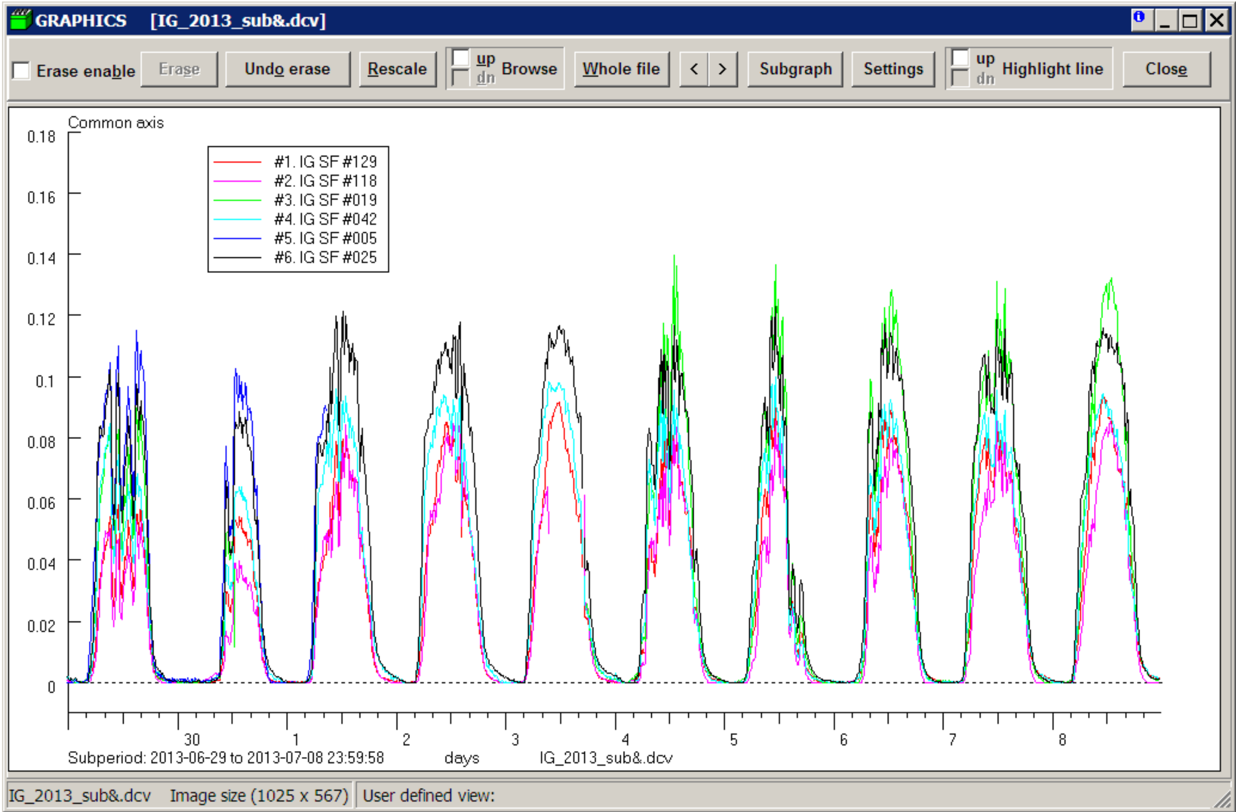
The right position of the 'subgraph' window on the screen has to be set manually, but the main advantage of this arrangement is that the time axis of 'subgraph' window moves synchronously with main graph. The whole working environment then looks like this:



The air humidity and precipitation variables were selected in the upper window. There are only a few nights with high air humidity and also only four rainy events with the 0.2 mm of precipitation only. The baseline created with respect to those weather conditions for selected subperiod of time is shown.

This process has to be done for the whole-time period and for all measured trees. Finished baseline has to be subtracted from each variable (offered in pop-up menu).

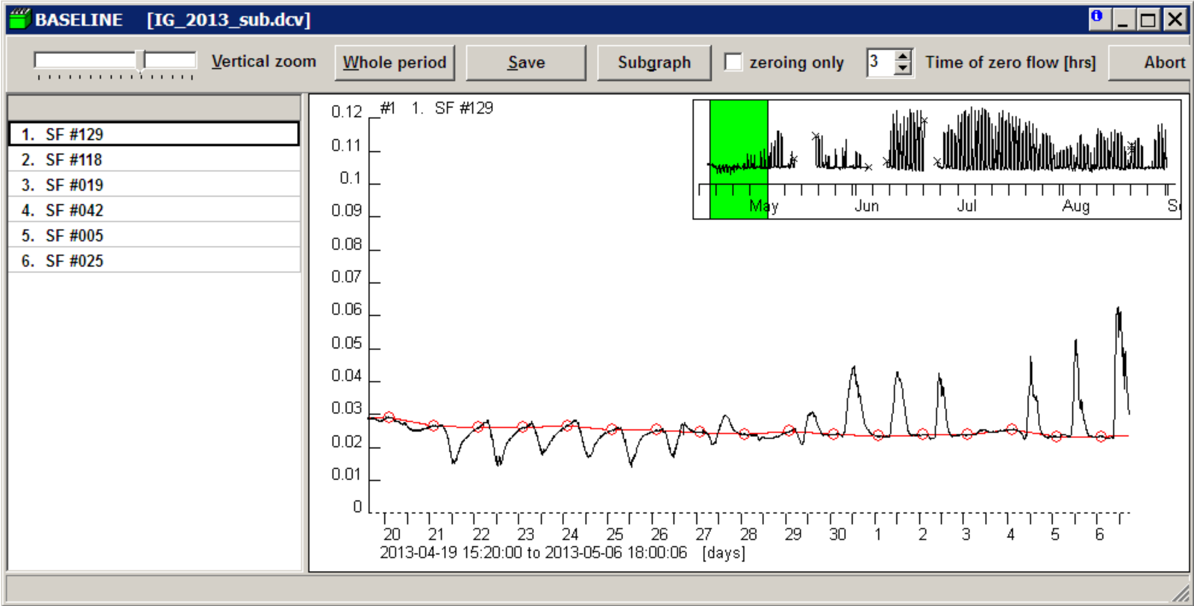
When all variables are processed, new file with '&' behind the filename is created and saved:



Baseline business is the trickiest part of data processing. The HB method working with low value of temperature difference (in order to save energy) is sensitive to external disturbing factors (like ambient temperature gradients, temperature inhomogeneities inside the measuring points etc.) under very low water movement.

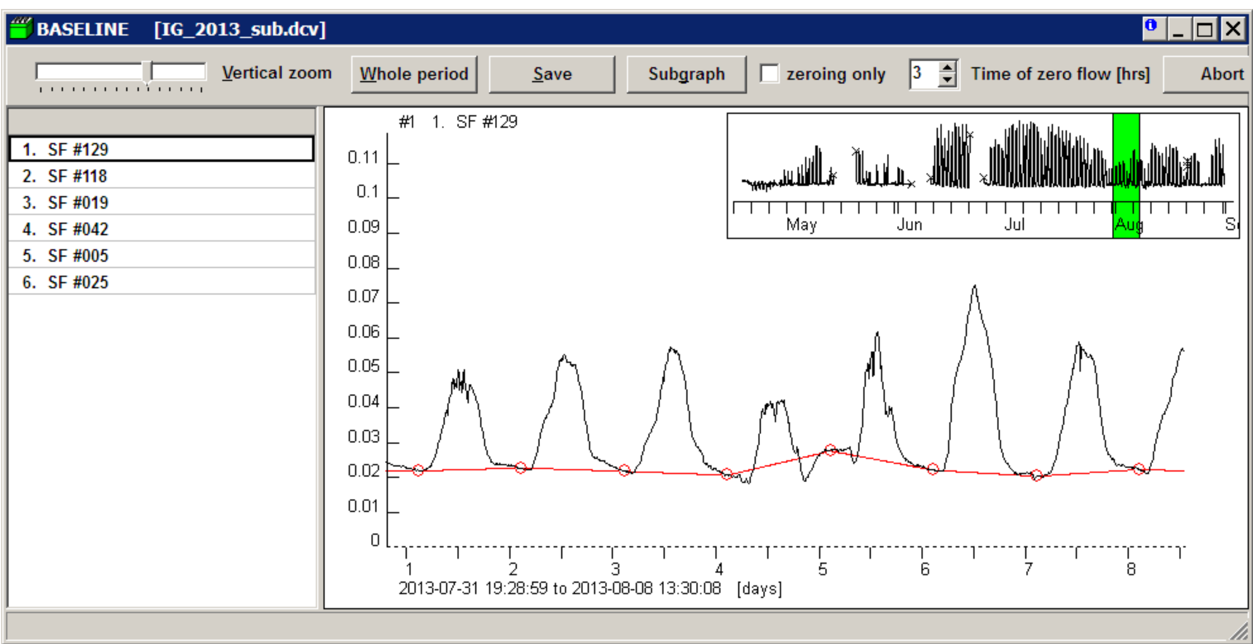
The baseline as the level of heat loss should be theoretically a straight line with little deviations due to change in stem water content and growth. However, some other factors like rain or fast temperature changes are interfering with theory. The only what really helps is practice and good understanding of the method.

Here are few examples which could help:

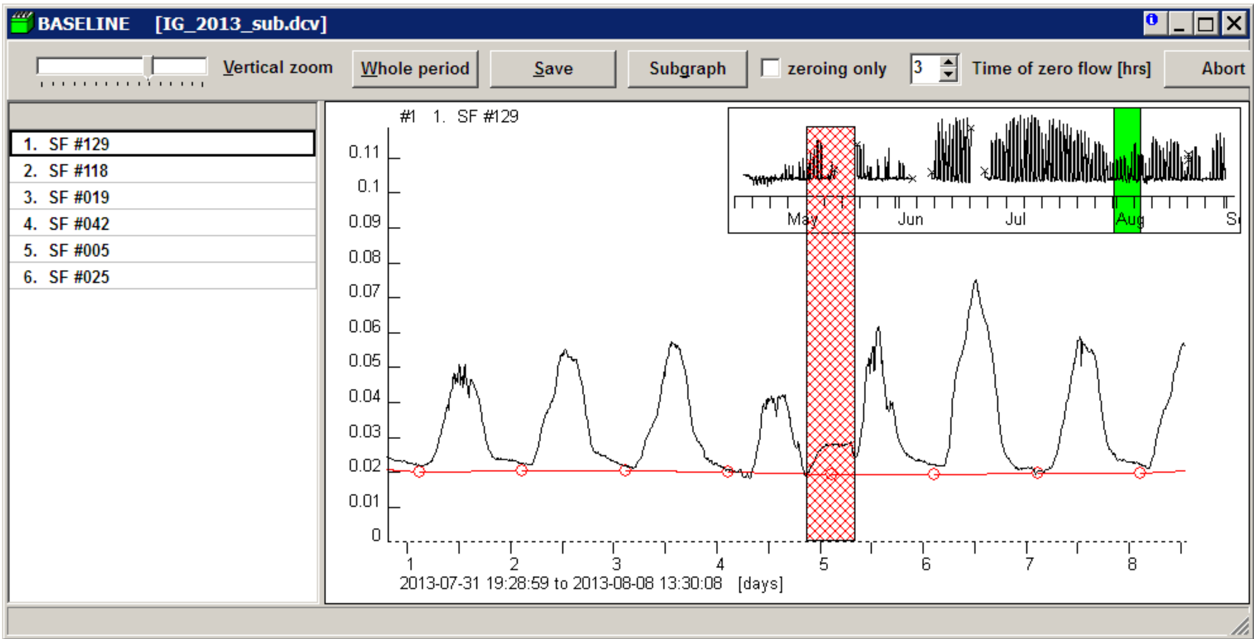


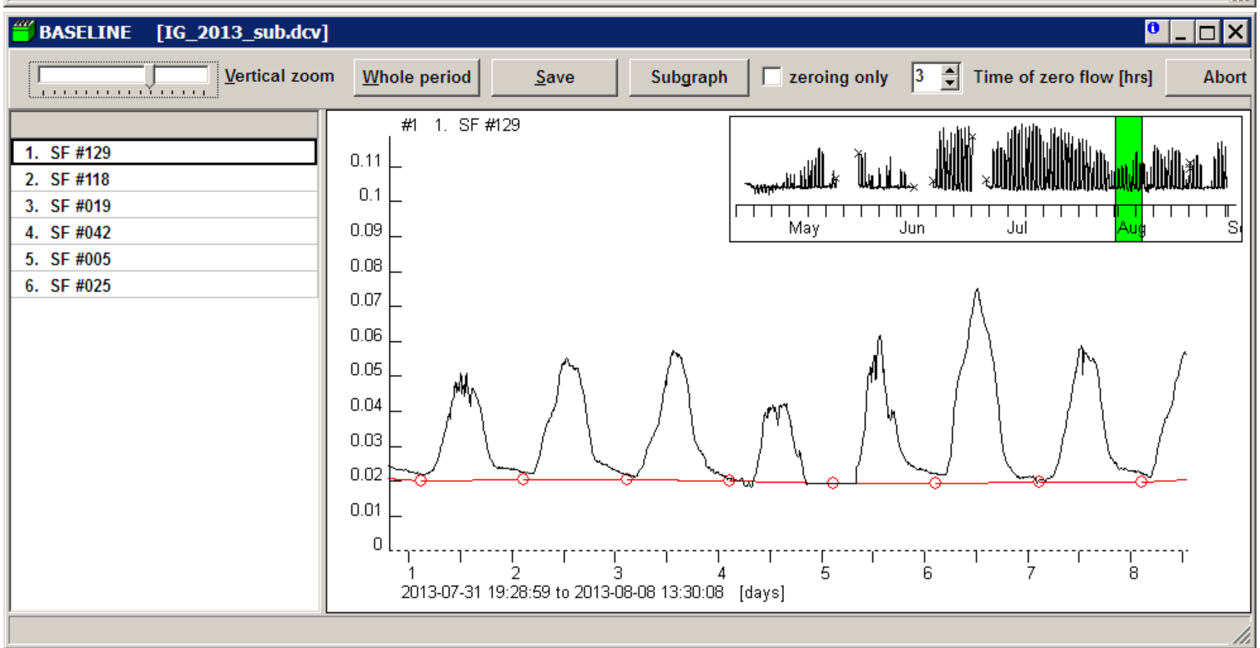
Typical situation at the beginning of growing season: European beech after the bud break. The strange pattern in days with 'negative' sap flow values can be explained by high vertical temperature gradient within the stem or outside. The system reduced power because this gradient helped to reach set temperature difference. The situation improved with the first leaves – the water stream 'smoothes' disturbing gradients.

Here the **stem flow** (beech!) disturbed the measurement:



The baseline has to be shifted downwards and the false night values have to be set to zero (mouse click + Ctrl):





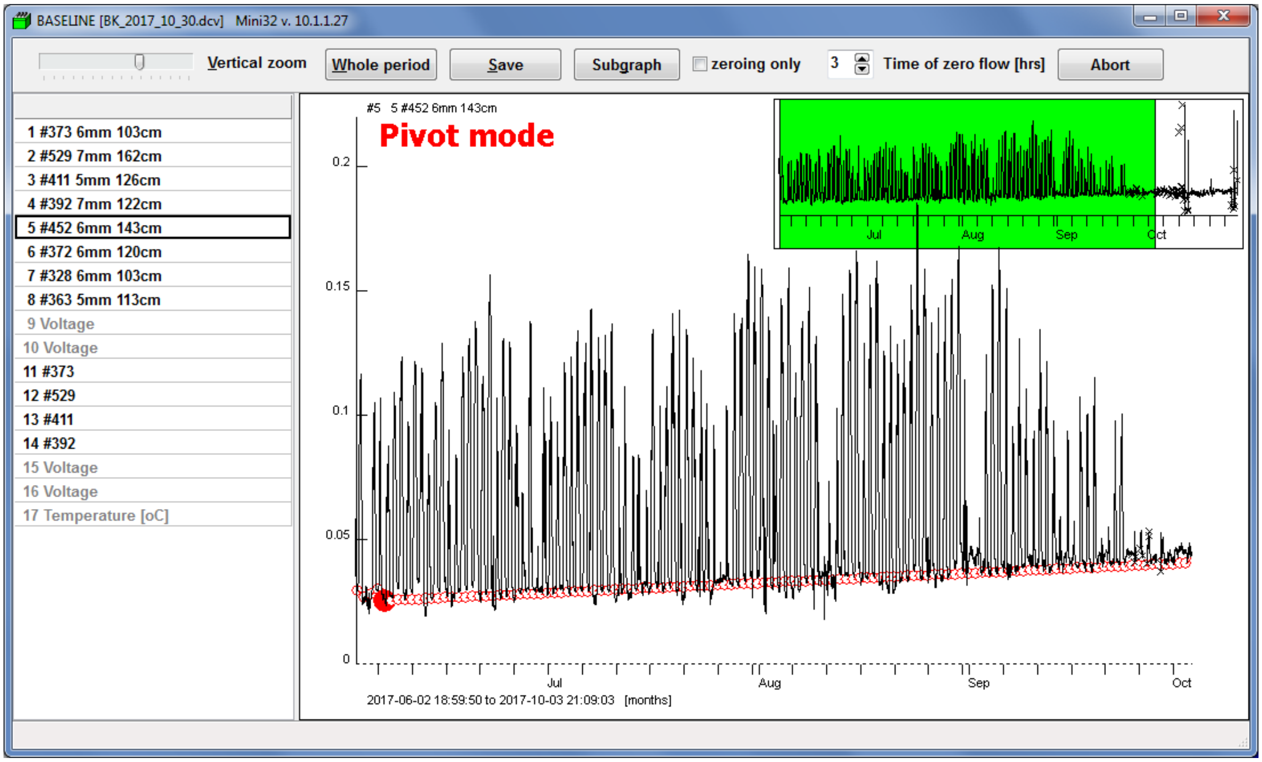
Note that the false values are not deleted but set to zero!

4.4.2.1.1. Pivot mode

The most recent approach to baseline is based on processing of huge amount of data files. The general idea is that the baseline should be straight line slowly rising up along the growing season due to radial increment.

The main exception is rainy period when the long-time period without a water movement allows the heat field reaches the reference electrode. Such a situation looks like virtual sap flow through all rainy days. In this time period the baseline should copy measured values.

For the fast construction of baseline based on previous assumption there is a trick: clicking on a circle with simultaneous pressing "Q" make a pivot. Shifting any other circle up or down will move the line anchored in pivot:



It depends on user how much time is he going to spend with baseline business. The night values with negligible sap flow rate are most vulnerable to influence of ambient temperature gradient. Therefore, there is rising a question whether the hard work with baseline has adequate effect.

4.5. Sensor dismounting

Sequence of dismounting operations:

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

See for installation guide for EMS 81 sap flow systems.

4.6. Maintenance

The 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 and brittle.

When the insulation of electrodes is too damaged, remove the rest of it by immersing them into spirit for a few hours. New isolation can be put on the electrodes with a special tool – ask manufacturer for tool and spare tapes.

5. Specification

5.1. Sap flow sensor SF 81

Measured values	kg h^{-1}, cm of stem circumference
Range	0 to 0.25 kg h^{-1} cm^{-1}
Heating	direct heating of stem tissues by passing of electrical a.c. current
Terminals/electrodes	three stainless plates 25 x 1 mm, 60, 70 or 80 mm long
Distance between electrodes	20 mm
Temperature sensors	thermocouples Cu-Co (T-type)
Thermosensor arrangement	three needles 1 mm in diameter placed in the middle of electrodes, one more as a reference
Controlled temperature	average of all three electrodes

6. Warranty

The producer warrants right function of the sap flow rate measuring device for three years after it is accepted by 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.