# Automated exponential feedback weighting method for subtraction of heat losses from sap flow measured by the trunk heat balance method

J. Kučera[1], R. Vaníček[2] and J. Urban[3,4,1]

[1]Environmental Measuring Systems, Brno, Czech Republic; [2]IVASOFT, Systems, Brno, Czech Republic; [3]Faculty of Forestry and Wood Technology, Mendel University in Brno, Czech Republic; [4]Siberian Federal University, Krasnoyarsk, Russia.

***Abstract***

**Removal of heat losses from the measuring point is one of the crucial issues during processing of data from the sap flow sensors, including the trunk heat balance method (THB). Heat losses (here referred to as 'baseline') are usually estimated at the time of presumably no sap flow. Three main issues may decrease the accuracy of the estimation of baseline: (i) existing sap flow in the night, which did not stop due to ongoing night transpiration or xylem refilling, (ii) natural temperature gradients between heated and reference part of the measuring point, and (iii) long-time (i.e. seasonal) changes in the heat losses due to stem growth or changes in the stem heat conductivity. Therefore, neither the estimation of baseline each night, nor its estimation as a lowest value in a specific (i.e. 2-week period) provide the correct result. Experienced users may be able to estimate the baseline manually (taking into consideration i.e. vapor pressure deficit) but this is a subjective and lengthy approach. Here we present an automated baseline subtraction based on the Exponential Feedback Weighting method. This method considers the nighttime sap flow, but it also removes outliers due to natural temperature gradients. We compared various averaging intervals of this method for the removal of baseline, from one day (i.e. estimation at every night) to 28 days in 1-day increments, estimation at the beginning and at the end of the season and manual subtraction by user (considering the weather data). Best results were provided by the 5-days weighting average, which was closest to the manual subtraction, and also provided enough flexibility for changes in baseline due to changes in the stem heat conductance.**

**Keywords:** sap flow, trunk heat balance method, baseline subtraction, heat losses

## INTRODUCTION

Trunk heat balance method (THB) (Čermák et al., 2004; Kučera et al., 1977) belongs to the group of heat balance methods (Čermák et al., 1973; Sakuratani, 1981) of sap flow measurements. Heat balance methods provide accurate estimates of the volumetric water flow (Schulze et al., 1985; Urban et al., 2012) and do not require a species- and site-specific calibration. In line, trunk heat balance method has been used to calibrate other (i.e. heat dissipation) sensors in the field (Klein et al., 2014; Lundblad et al., 2001). Main reasons for the high accuracy of the trunk heat balance method are (Tatarinov et al., 2005): (i) direct heating of the xylem by the electric current which avoids conduction of heat between metallic heater (i.e. needle) and the xylem makes the THB method accurate for large flows, making it suitable for measurements even on the ring porous species, (ii) measurement of the large volumes of the xylem, which makes the method robust against circumferential heterogeneities in the sap flow, (iii) averaging the radial profile of the entire sapwood by the large and highly heat-conductive stainless steel plates inserted into the sapwood, which provides one integral value of the sap flow for the entire sap wood profile. Furthermore, recent improvements on the method, such as maintaining constant temperature difference between the heated and the

[1]E-mail: josef.urban@email.cz

reference part of the measuring point, made the THB methods power efficient and improved sensitivity and response time to the fast changes in the sap flow (Kučera and Urban, 2012).

Crucial for the accuracy of the estimation of sap flow by THB method is removal of dissipative heat losses from the measuring point (further referred to as 'baseline subtraction'). The sap flow ($Q$) is calculated from the heated power as:

$$Q = \frac{P}{c_w * dT * d} - \frac{\lambda}{c_w} \tag{1}$$

where $P$ is an input power, $dT$ is a temperature difference between heated part of the measuring point and surrounding xylem, $d$ is the width of measured segment, $c_w$ is a specific heat of water and λ is the heat loss from the measuring point. All the above-mentioned variables are physically defined constants or they are automatically measured, except λ, which is estimated during the data processing. The λ is usually estimated as the amount of heat needed to maintain constant $dT$ when no sap flow occurs. Often, the lowest value from the previous night is subtracted (Langensiepen et al., 2014). But naturally, zero flow does not occur every night since the trees transpire in the night upon non-zero vapor pressure deficit (VPD) (Kavanagh et al., 2007; Zeppel et al., 2012) or the water storage compartments do not completely refill at night (Čermák et al., 2007; Goldstein et al., 1998). Therefore, lowest sap flow value in a longer time period or more complicated methods based on the night minimal VPD are used (Hoelscher et al., 2018). However, temperature gradients within the measuring point occurring only in some nights dampens the accuracy of estimation of the heat losses (Do and Rocheteau, 2002). Therefore, the lowest sap flow value in a longer period may underestimate the real heat losses and overestimate the real sap flow. The temperature gradients in the night probably stem from the axial gradient of air temperature combined with varying radial thermal conductance of xylem between heated and a reference part of the stem. Because they differ among the trees and even within a single stem, there is no simple way to correct them during the measurement. The effect of the natural temperature gradients on the measured sap flow is highest at night and it decreases with increasing sap flow in the day (Figure 8 in Tatarinov et al., 2005) (Figure 1). In line, the error of estimation of the sap flow in the day caused by natural temperature gradients is lower than their effect on the baseline. It follows that the baseline value shall be estimated for the long time period, but the lowest value of the heat loss may be influenced by natural temperature gradients which do not as much affect the estimate of day flows. At the same time, the baseline may stay the same for the entire vegetation season, but sometimes it may also have increasing or decreasing trends due to long-time changes in the stem heat conductance.

The perfect method to estimate the baseline shall therefore (i) accounts for the night sap flows, (ii) allows for the seasonal increasing or decreasing trend in the baseline and (iii) minimizes the effect of occasionally occurring temperature gradients on the baseline. Here we present an automated method of baseline subtraction based on Exponential Feedback Weighting algorithm which aims to fulfill all three above-mentioned criteria. We aim that the method will automatically remove the baseline while retaining the night sap flow (i.e. avoiding underestimations from identifying the heat losses on a day-to-day basis) but avoiding overestimation caused by incorrect consideration of the natural temperature gradients.

## MATERIALS AND METHODS

### The description of procedure of Exponential Feedback Weighting method

Exponential Feedback Weighting takes into account sap flow value each day at 4:00 am (shown as Yt in Equation 3). Such values are smoothed using exponential moving average (EMA) with the alpha factor computed as shown in Equation 2 using N=5 (optional). All past values have a non-zero weight, however the sum of weights of N newest values is 99.9% of the total weight. Subsequent sap flow base value at time t is calculated from Yt and previous sap flow base value St-1 as shown in Equation 3.

$$a = \frac{2}{N+1} \quad (2)$$

$$S_t = \begin{cases} Y_1, & t = 1 \\ \alpha Y_t + (1-\alpha) S_{t-1}, & t > 1 \end{cases} \quad (3)$$

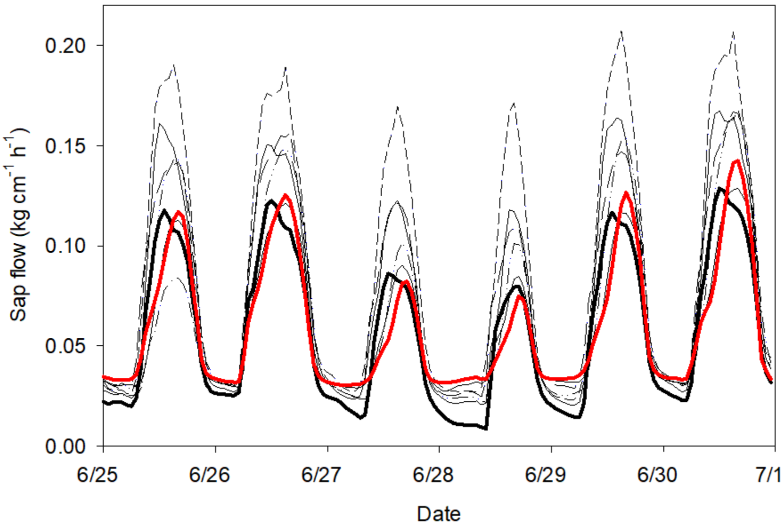


Figure 1. An example of diurnal curves of sap flow of the individual trees from the European beech stand. Two selected trees are indicated by the thick line and color transpire similar amounts of water per unit of stem circumference but the baseline (night heat loses) of only one of them is affected by the natural temperature gradient. Note that, unlike the baseline, the daily maximums remain unaffected.

**Field measurements**

The stand under study is located in the Czech Republic in the Ore Mountains near the German border, close to the village of Načetín (50°35’26”N, 13°15’14”E). The average annual temperature is 7.1°C, and average annual precipitation is 1110 mm (2005-2017). The dominant soil type is dystric cambisol. The beech stand is situated at an elevation of 823 m a.s.l. and is composed predominantly of European beech trees (*Fagus sylvatica*) that are approximately 140 years old. We selected this particular site for the demonstration, because the effect of natural temperature gradients on baseline was particularly large, comparing to most of the sites and trees in our database. Also, importantly, as we demonstrate in Figure 1 the effect of temperature gradients on the baseline differed between the trees.

Eight trees with diameters ranging from 32 to 52 cm were selected for sap flow measurements. We used the segment trunk heat balance (THB) method (Čermák et al., 1973, 2004). The sap flow sensors (EMS-51A, EMS Brno, Czech Republic) were installed at breast height, one on each of trees and covered with a reflective weather shield. The voltage outputs of the sensors were registered by the data logger (Railbox V16, EMS Brno, Czech Republic) at one-minute intervals, and 10-min averages were stored in the memory. Sap flow and stem increment were measured for the entire vegetation season in 2019.

**Removal of baseline by various methods**

Heat loses from the measuring point (baseline) were removed by automated and manual means. The automated way used the above described Exponential Feedback Weighting method. We used averaging intervals (parameter $N$ in Equation 2) of 1 day (no averaging, the baseline was estimated every day as the power input at 4 am), 3, 5 and 28 days. Manual removal of the baseline was done by an experienced user based on a subjective decision, supported by the current weather data, especially vapor pressure deficit. User decided on baseline level based on nights when VPD approached zero. Effect of stem refilling on baseline was estimated by comparing long-term rainy periods with nights when VPD was zero. Baseline in other trees in the forest stand was considered, too. Due to all these considerations, albeit subjective, the manually determined baseline was used as a reference for automatic baseline subtractions. All analysis was done in Mini32 software (EMS Brno, Czech Republic). We analyzed data for entire season 2019, which we present in Figure 2 and in Table 1. Diurnal curves of sap flow in Figures 1, 3, 4 and 5 are demonstrated on a shorter period from 25 to 30 June 2019, when the baseline of some trees was affected by unusually large natural temperature gradients and when also the nights with non-zero vapor pressure deficit occurred.

Table 1. Absolute values of differences between each of the four averaging intervals of automated baseline subtraction and a manual method. Differences are expressed as absolute sap flow value and as a percentualage difference compared to the daily mean sap flow of 0.55 kg cm$^{-1}$ day$^{-1}$ (i.e. variation coefficient).

| Description | Variation coefficient (%) | Average difference (kg cm$^{-1}$ day$^{-1}$) |
|---|---|---|
| 1 day average | 5.04 | 0.0277 |
| 3 day average | 3.22 | 0.0177 |
| 5 day average | 2.91 | 0.0160 |
| 28 day average | 5.72 | 0.0315 |

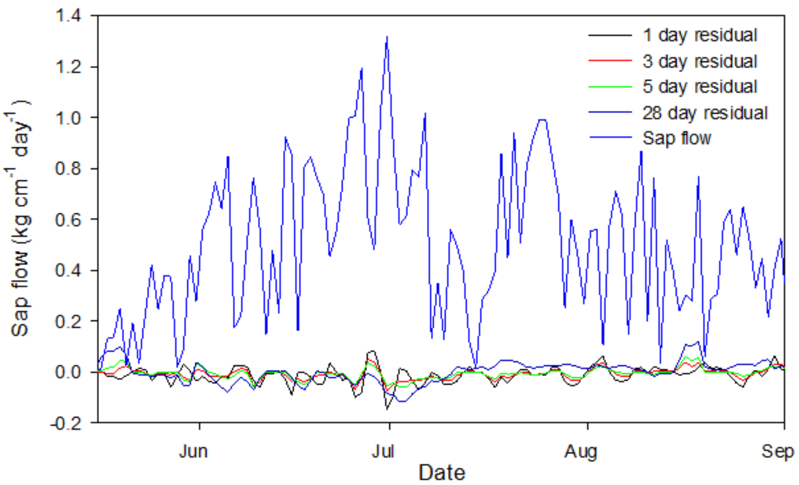


Figure 2. Differences between daily sums of sap flow estimated using four different averaging intervals of automated baseline subtraction (i.e. residuals) and sap flow estimated using manual baseline subtraction. Data are compared to the total sum of sap flow (kg cm$^{-1}$ of stem circumference day$^{-1}$).

## RESULTS AND DISCUSSION

Air temperature within the trial period where we demonstrate diurnal curves of sap flow, from 25 June to 30 June 2019, varied between 9.6 to 32.6°C with an average 21°C (Figure 3). Air humidity varied between 16 and 100%. The days were almost cloudless (except the morning of 28 June) and without precipitation.

The heat losses (i.e. the lowest recorded value of sap flow before baseline subtraction at 4am) from the sap flow measuring point in the night were similar in all trees in the beginning and at the end of the trial period but differences between the trees increased in the middle of the period (Figure 1). While the baseline in most of the trees remained similar, in some trees decreased. It indicated occurrence of natural temperature gradients (Do and Rocheteau, 2002) which affected the heat losses and decreased the energy needed to maintain constant temperature difference between the heated and the reference part of the measuring point.

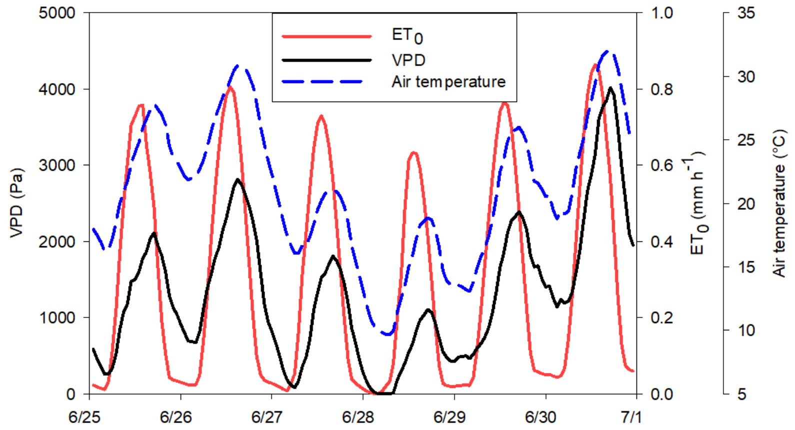


Figure 3. Weather data from the trial period (same period as in the Figure 1): Penman-Monteith based reference evapotranspiration ($ET_0$), vapor pressure deficit (*VPD*), and air temperature.

Various averaging methods accounted for the variation in the baseline in different ways (Figure 4). Within the trial period with large changes in baseline, the closest to the manual removal, with 1% underestimation of the sap flow was the 5-days averaging method (Figure 5, Table 2), which is also the recommended averaging period in the Mini32 software. The highest underestimation of 3% was achieved with the 1-day averaging. Also, the longest interval of averaging, 28 days, underestimated the sap flow by almost 3% indicating that some flexibility in the estimation of baseline is desired due to seasonal changes in the heat losses from the heated part of the stem due to changes in stem heat conductance. Results for the entire vegetation season 2019 were similar to the short period (Figure 2, Table 1). The lowest differences between automated and manual baseline removal were found for the 5-day averaging period and largest for the one and 28 day long averaging periods.

To conclude, automated Exponential Feedback Weighting method removed heat losses from the data with similar accuracy as an experienced user. The recommended averaging period for the removal of the baseline is ca. 5 days. Selection of too short period removes part of existing night fluxes. On the other hand, too long averaging interval lacks the flexibility to describe short-term changes in heat losses.

Table 2. Table of regression parameters and coefficients of correlation between sap flow with manually subtracted baseline and various averaging periods used for automated Exponential Feedback Weighting method. Data are depicted in the Figure 4. The equation $y=B*x$ is used.

| # | B | $R^2$ | Average length (day) |
|---|---|---|---|
| 1 | 0.971913 | 0.987254 | 1 |
| 2 | 0.987016 | 0.996376 | 3 |
| 3 | 0.990993 | 0.99818 | 5 |
| 4 | 0.972132 | 0.998455 | 28 |

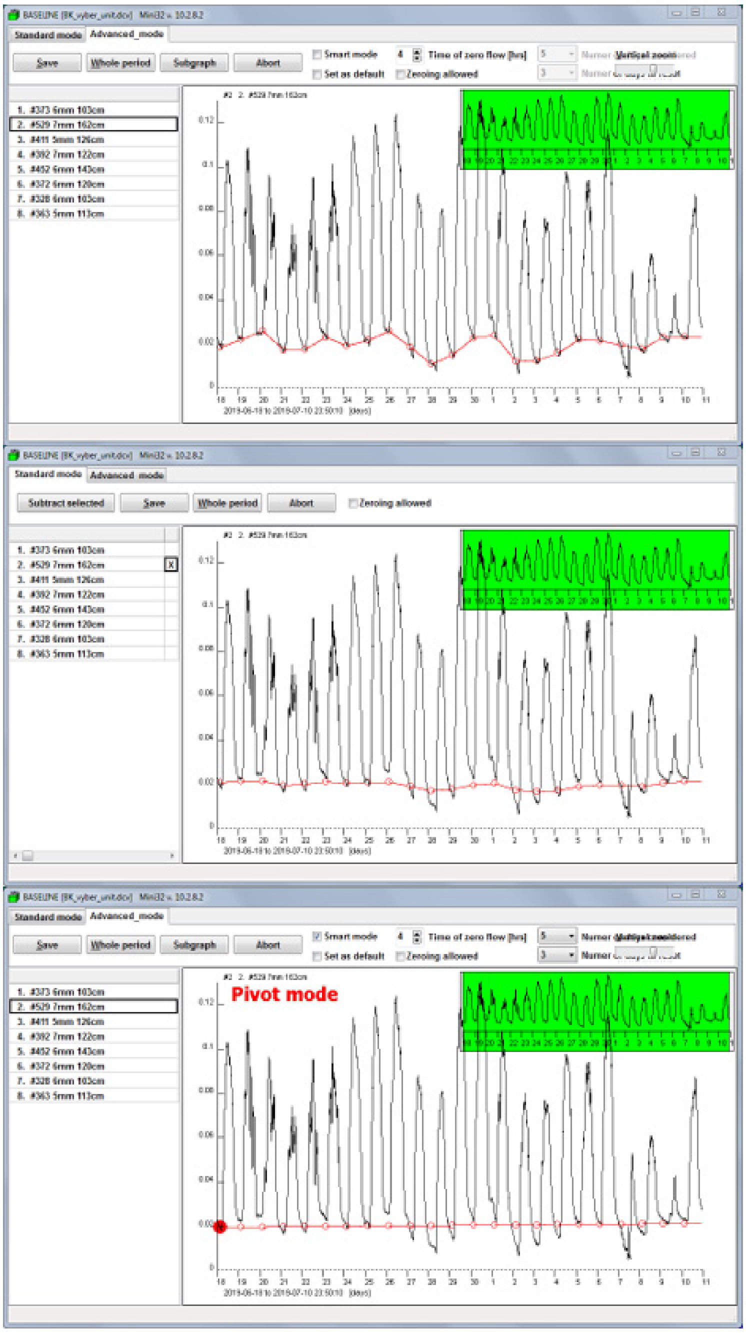


Figure 4. Effect of various averaging intervals used for the Exponential Feedback Weighting method used to subtract the baseline from the sap flow in European beech. From the top: averaging intervals of 1 day (i.e. estimation of baseline on the day-to-day basis), 5 days (which is used in the standard mode in the Mini32 software for processing of the THB sap flow data), and the straight line for entire period of baselining. For illustrative purposes (because the baseline is estimated based on the long period), we show longer period than in the Figures 1, 3 and 5, from 18 June to 10 July 2019, when unusually large variation in the baseline occurred.

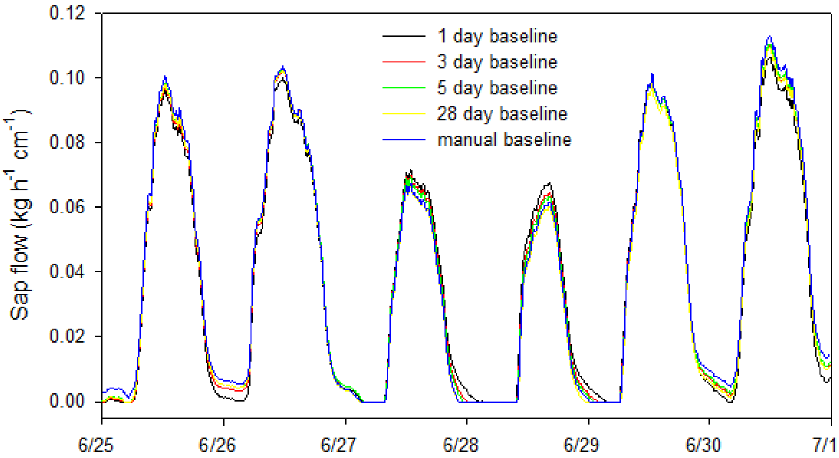


Figure 5. Comparison of effect various averaging intervals (1, 3, 5 and 28 days) of the automated baseline removal and manual removal based on the decision of user, considering night vapor pressure deficit, on the estimated sap flow of the tree from the Figures 1 and 4. Inset shows correlation between manual subtraction and various automated estimations of baseline.

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