# TRIAL OF IDENTIFICATION OF A SOLAR RADIATION TRANSMISSION FORMULA WITHIN SPRUCE TREE STAND

**Józef Suliński [1], Przemysław Sypka [2]**

[1] Department of Forest Engineering, Faculty of Forestry, Agricultural University
al. 29 Listopada 46, 31-425 Kraków
[2] Department of Electronics, University of Mining and Metallurgy
al. Mickiewicza 30, 30-059 Kraków

**Abstract**

It was proved that a variability of solar radiation transmission coefficient within tree stand may be explained by biometric features of tree stand. Formulas, which described this relationship, were based on the Beer's law and ecological criteria connected with the dynamics of tree stand growth. Empirical data obtained in Istebna spruce stand (Beskid Śląski) were used for formulas' identification.

## INTRODUCTION

The quantity of radiation's energy reaching the surface of the soil in a forest is (besides the wind velocity and the soil humidity) the main factor, deciding upon the amount of water evaporating from inter-particle spaces of the soil. In turn, the vaporisation from the soil has a basic significance for the components of water exchange balance between the atmosphere, tree stand, and the soil in various forests. The specific of radiation energy measurements inside tree stand is related to the uneven vertical distribution of biomass.

The silvicultural practices, which affect the amount of biomass located in various layers of tree stand, may influence the quantity of solar radiation's energy reaching forest floor level. If an energy balance within forest community is well known as a physical process, there are still no formulas combining the variability of balance components with the biometric features of the tree stand. Such equations are essential for forest practice to anticipate and to describe effects of silvicultural practices. Methodological and organisational difficulties of conducting measurements within forest communities, essential for identification of theoretical models, and the lack of a knowledge on dynamics of tree stand, particularly the rules of filling forest space by biomass [4], are the main obstacles to define the necessary formulas.

In previous paper authors presented theoretical assumptions for research on energy balance within spruce tree stand [1]. The conclusion was that, among other things, an empirical equation based on the Beer's law, expressing solar radiation transmission coefficient within tree stand consisting of three layers: crowns, stems and forest floor vegetation:

$$\frac{I_l}{I_t} = (1-\alpha_c)\cdot(1-\alpha_s)\cdot(1-\alpha_g)\cdot e^{-(\mu_c\cdot h_c+\mu_s\cdot h_s+\mu_g\cdot h_g)} \quad (1)$$

where: $I_l$ - intensity of radiation at the level of litter, $I_t$ - intensity of radiation above the crowns layer, α - reflection coefficient for each of the layers (c - crowns, s - stems, g - ground coverage), μ - absorption coefficient for each of the layers respectively, h - the height of the layer.

This paper continues the issue of a short waveband energy radiation in forest community. The objective of the paper is to adapt equation (1) to conditions occurring inside experimental spruce tree stand and its identification based on measurement results of solar radiation intensity and biometric features.

## RESULTS OF FIELD MEASUREMENTS

All measurements were organised by Department of Forest Engineering of Cracow Agricultural University in the areas of experimental catchment „POTOK DUPNIAŃSKI", located in Beskid Śląski Mountains [6]. It is a part of research on water balance of Istebna spruce stands. Measurement points were located within four spruce stands of various ages and on the two open fields. There was no ground cover in vicinity of measurement points, so the solar radiation intensity was gauged at the height of 2 meters and 0,3 meters (Fig. 1); on the open fields at the height of 9 meters above the ground.

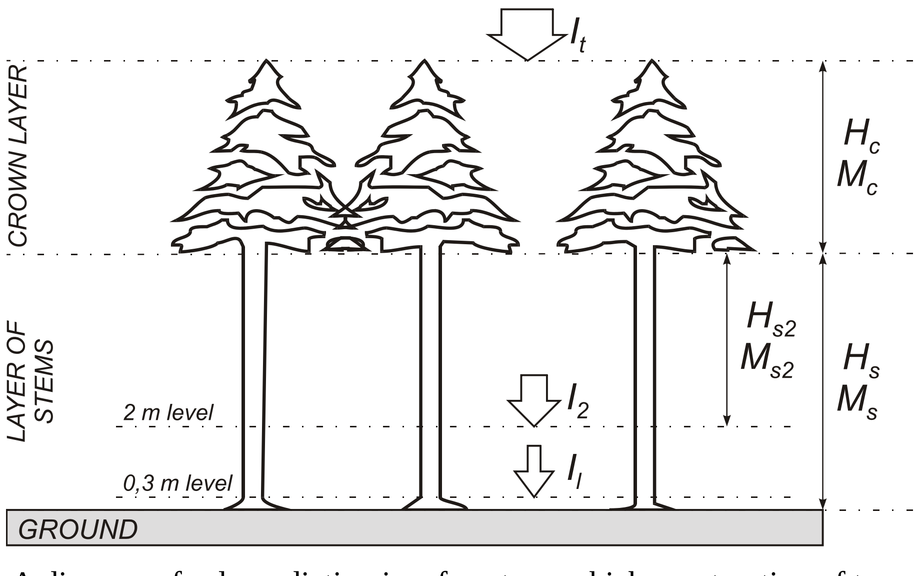


**Fig. 1**. A diagram of solar radiation in a forest, on which construction of transmission equation was based.

$I_t$ – solar radiation intensity over tree crowns; $I_2$ – solar radiation intensity at the height of 2 meters; $I_l$ – solar radiation intensity on the litter level; $H_c$ – the height of the layer of tree crowns; $H_s$ - the height of the layer of stems; $H_{s2}$ - the height of the layer of stems diminished by 2 meters; $M_c$ – mass of the layer of the tree crowns; $M_s$ – mass of the layer of stems; $M_{s2}$ – mass of the layer of stems above the height of 2 meters over ground

Silicon semiconductor sensors were used to measure solar radiation intensity. The sensor active band is from 0,3 μm to 1,3 μm and it gauges about 70% of total solar radiation spectrum. This method of measurement is completely insensitive to temperature variation, i.e. long wavelength of the Earth and atmosphere's back radiation. All sensors were placed horizontally. Measurements were automatically taken every 6 minutes. Data presented in this paper were obtained in four different periods of the year 1999. Example data of solar radiation intensity, gauged on the 1st of May 1999 in thicket, are shown on Fig. 2.

**Table 2. V**alues of solar radiation intensity and transmission coefficient.

| Sum of values of solar radiation intensity [W/m$^2$] | | | | | | |
|---|---|---|---|---|---|---|
| Month of year 1999 | on the open-air fields | | research station within tree stand, on the height of | | | |
| | valley-bottom mountain-meadow | average value | 2 m<br>0,3 m | 2 m<br>0,3 m | 2 m<br>0,3 m | 2 m<br>0,3 m |
| | | | thicket | pole-size stand | mature forest | mature forest |
| February | 42220<br>43930 | 43075 | 34610<br>- | 656<br>- | -<br>3058 | 5394<br>1849 |
| March | 64782<br>58910 | 61846 | 40010<br>- | 1488<br>154 | -<br>4764 | 5695<br>4519 |
| May | 53449<br>49687 | 51568 | 33440<br>13726 | -<br>1100 | 3938<br>3929 | 3980<br>5058 |
| July | 43401<br>41972 | 42687 | 35078<br>8845 | 1270<br>1274 | 4933<br>3336 | 4292<br>3014 |
| August | 200091<br>106434 | 153262 | 155246<br>36658 | 4230<br>2729 | 18741<br>15768 | 16900<br>13555 |
| September | 126878<br>114843 | 120861 | 118753<br>22147 | 2018<br>1874 | 11558<br>11273 | 11677<br>10770 |
| Calculated values of energy transmission coefficient: $C_2$ (2 m) and $C_l$ (0,3 m) | | | | | | |
| February | | | 0,803<br>- | 0,015<br>- | -<br>0,071 | 0,125<br>0,043 |
| March | | | 0,647<br>- | 0,024<br>0,003 | -<br>0,077 | 0,092<br>0,073 |
| May | | | 0,648<br>0,266 | -<br>0,021 | 0,076<br>0,076 | 0,077<br>0,098 |
| July | | | 0,822<br>0,207 | 0,030<br>0,030 | 0,116<br>0,078 | 0,101<br>0,071 |
| August | | | 1,013<br>0,239 | 0,028<br>0,018 | 0,122<br>0,103 | 0,110<br>0,088 |
| September | | | 0,983<br>0,183 | 0,017<br>0,016 | 0,096<br>0,093 | 0,097<br>0,089 |

Transmission coefficients were calculated as a ratio of a sum of solar radiation intensity on described level within tree stands to the analogous sum in the open field. This procedure reduces the possible influence of clouds on variation of solar radiation intensity in different checkpoints in the catchment. It was not necessary to carry out any standardisation to eliminate the effects of location of dependence of the measurements points on valley slope, because all sensors gauged the intensity of solar radiation for the horizontal surface. Only the sums of solar radiation intensities over tree crowns were calculated as average values of data from the measurement points in the open. This simplification limits a variability of solar radiation intensity resulting from possible shadings of the valley slopes. The values of solar radiation transmission coefficient and basic data are shown in Tab. 1.

The breast height diameters and heights of trees in experimental tree stands were recorded around the measurement points. Next, tree stand's biometric features, necessary to the identification of investigated formula, were calculated by the method described in [4]. The results (standardized for 1 ha) are shown in Tab. 2.

**Table 2.** Empirical data and calculated biometric features of experimental tree stands.

| Tree stand | | N | D | H | $Z_m$ | $H_c$ | $H_s$ | $M_t$ | $M_c$ | $M_s$ | $M_{s2}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| thicket | A | 14600 | 3,9 | 4,6 | 0,89 | 2,0 | 2,6 | 90 | 56 | 34 | 7 |
| | B | 41600 | 1,3 | 0,9 | | | | | | | |
| pole-size stand | | 2580 | 11,8 | 12,8 | 0,79 | 5,3 | 7,5 | 222 | 156 | 66 | 26 |
| mature forest | | 360 | 40,2 | 36,2 | 0,80 | 15,0 | 21,2 | 637 | 369 | 268 | 199 |
| mature forest | | 340 | 43,5 | 36,7 | 0,85 | 14,6 | 22,1 | 690 | 369 | 321 | 245 |

*N* – number of trees per 1 ha; *D* – average diameter of the breast height [cm]; *H* – average height [m]; $Z_m$ – density by Suliński equation [4]; $H_c$ – the height of the layer of tree crowns [m]; $H_s$ - the height of the layer of stems [m]; $M_t$ – total mass of all trees with leaves [t/ha of fresh mass of over-ground parts of plants]; $M_c$ – mass of the layer of the tree crowns [t/ha of fresh mass]; $M_s$ – mass of the layer of stems [t/ha of fresh mass]; $M_{s2}$ – mass of the layer of stems above the height of 2 meters over ground [t/ha of fresh mass]

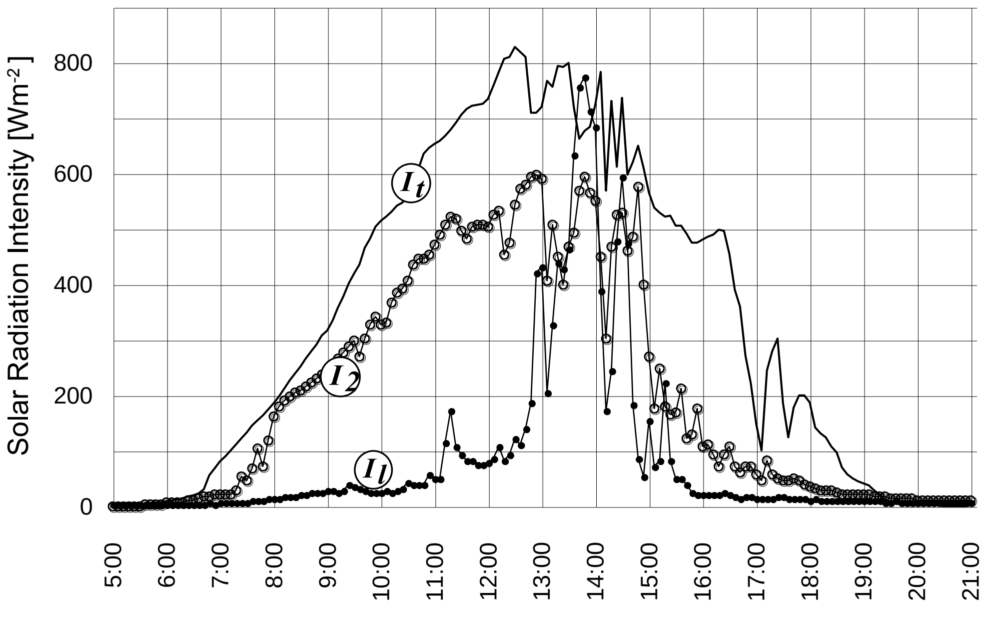


**Fig. 2.** Example of changes in solar radiation intensity in time.

## STRUCTURE OF FORMULA AND ITS IDENTIFICATION

The biomass filling the volume, occupied by a forest community (calculated from ground level to tops of trees) has an ability to absorb solar radiation in different degree. There are premises that the ability of absorption depends mainly on the concentration of biomass in specific layers of tree stand [2][5][1]. This concentration, expressed as a ratio of the amount of biomass to the height of the layer, may be equivalent to the absorption coefficient $\mu$ in the Beer's law (1).

By analogy to results of research in meteorology it was assumed that an elevation of layer of biomass above the surface of the ground may have an influence on the quantity of absorbed solar energy. In experimental tree stand it is possible to separate two layers: crowns and stems; ground litter practically does not occur. The elevation of crowns is equal to the length of the stems (Fig. 1.), so the term $(2 - H_s^/)$ was inserted in formula (2).

Based on indexing variable (all values of variable are divided by its maximum value), with reference to solar radiation transmission to the litter level, the following form of formula was assumed:

$$C_l = \frac{I_l}{I_t} = \delta \cdot e^{-\beta \cdot (2 - H_s^/) \cdot M_c^/ - \gamma \cdot M_s^/} \quad (2)$$

where: $C_l$ - coefficient of radiation transmission to the litter level; $I$ - solar radiation intensity [W/m$^2$]: $l$ - on the litter level; $t$ - over tree crowns; $M^/$ - mass of plants [t of fresh mass/ha] (*indexing variable*): $c$ - in the layer of crowns, $s$ - in the layer of stems; $H_s^/$ - the elevation of tree crowns base over the ground [m]; δ, β, γ - coefficients to be estimated during the identification of the equation.

The corresponding equation, which defines the transmission of solar radiation to the level of 2 meters above ground surface, has the form:

$$C_2 = \frac{I_2}{I_t} = \delta \cdot e^{-\beta \cdot (2 - H_s^/) \cdot M_c^/ - \gamma \cdot M_{s2}^/} \quad (3)$$

where: $C_2$ - coefficient of radiation transmission to the level of 2 meters above ground surface; $I_2$ - solar radiation intensity on the height of 2 meters above ground surface [W/m$^2$]; $M_{s2}^/$ - mass of tree stems diminished by mass of 2 meters height' parts of stems [t fresh mass/ ha] (*indexing variable*); remaining symbols as in (2).

Identification of formulas (2) and (3) was based on the data shown in Tab. 1. and Tab. 2. The results of an identification are presented in Tab. 3. The equation (2) explains 82% of the variability of solar radiation transmission coefficient to the forest litter in experimental spruce stands. The equation (3) explains the variability of solar radiation transmission coefficient to the height of 2 meters above ground surface in 94%. In both cases matching tests of empirical data, calculated according to the formulas, prove that the form of transmission equation was correctly matched. Large values of a standard deviation of estimation - 33% and 30% respectively (Tab. 3.) – may be explained by the measurement conditions:

- formally, sufficient number of cases used to the identification ($n$=21) came from only four tree stands, so the diversity of conditions of solar radiation transmission, defined by explaining variable $M$ and $H$, was relatively small,
- the highest variability of values of transmission coefficient was observed in the thicket; it could be connected with difficulties in choosing the right place for placing the sensors, so in consequence the relationship between gauged solar radiation intensity and biometric features, describing transmission conditions of solar radiation within thicket, was disturbed,
- the best solution would be a direct measurement of solar radiation intensity over tree crowns on the monitoring stations, not only on open fields; it was impossible in the this research for technical and organisational reasons,
- in addition to the above, the calculated values of radiation energy transmission are biased with an error of periodical shading of sensors by mountain ridges and tree stands surrounding the measurement points; a shortened time of radiation intensity accumulation which could be used for calculation of transmission coefficient values might eliminate this error significantly, at the cost of increased error associated with an

irregular sky cloudiness.

**Table 3.** Coefficients used in formula [2] and [3]; values of matching tests of C computed using the formulae and the measured ones.

| *Number of formula* | *Coefficients* | | | *Number of cases* | *Coefficient of multiple correlation* | | *Standard error of estimation* | *Coefficient of variaton* [%] | *Mean deviation* |
|---|---|---|---|---|---|---|---|---|---|
| | $\delta$ | $\beta$ | $\gamma$ | | *R* | *100R*$^2$ [%] | | | |
| [2] | 0,62 | 4,63 | 2,70 | 21 | 0,908 | 82,5 | 0,0304 | 32,8 | 0,00071 |
| [3] | 6,57 | 3,58 | 6,57 | 21 | 0,971 | 94,3 | 0,085 | 29,5 | 0,0035 |

## CONCLUSIONS

1. Presented formulas take into consideration the most important factors, which determine short waveband energy transmission of solar radiation within tree stands. This form of equation applies to the transmission of solar radiation through two layers of biomass, but by analogy it could be applied for tree stands including more layers, for example shrub layer and forest floor vegetation.
2. Structure of the formulas, based on the Beer's law and ecological criteria resulting from dynamics of tree stand growth, permit an attempt to identify these formulae for stands composed of other tree species. In this case it is essential to calculate the values of transmission coefficient as ratios of radiation intensities, measured for the horizontal surfaces. This condition may be met by adequate setting of measurement sensors, or by application of conversion formulas.

## REFERENCES


[1] J. Suliński, P. Sypka: „Assumptions for Interpretation of Measurements of Energy Radiation within Tree Stand", Proceeding of the III National Conference „Application of Mathematics in Biology and Medicine", Mądralin 1997.

[2] M. S. Czarnowski: „Zarys ekologii roślin lądowych", 1978.

[3] S. Eagleson: „Hydrologia dynamiczna", PWN, Warszawa 1978.

[4] J. Suliski: „The Amount of Biomass as a Function of the Height and Density of a Tree Stand", Proceeding of the III National Conference „Application of Mathematics in Biology and Medicine", Mądralin 1997.

[5] J. Suliński: „Modelowanie bilansu wodnego w wymianie między atmosferą, drzewostanem i gruntem przy użyciu kryteriów ekologicznych", Zeszyty Naukowe AR Kraków, rozpr. 179, 1993.

[6] P. Sypka: „The Catchment Monitoring System", Proceeding of the International Scientific Conference „FOREST AND WATER", Kraków 1998.