Absorption of light

OBJECTIVE

To examine the attenuation of the visible light by the set of transparent plates.
To measure the intensity of the transmitted light vs. thickness and number of elements absorbing glass plates. The collected data are analyzed in terms of the exponential Beer-Lambert's law of absorption. The absorption coefficient of the transparent material is to be established.

CONTENTS

I. Theory.
- **A. Basic concepts of Radiometry and Photometry**
- **C. Absorption of light by the set of transparent plates.**

II. Apparatus for the experimental exploration.
III. Data acquisition.
IV. Data analysis (TI83)
V. Data analysis (MS Excel)

THEORY

A. Basic concepts of Radiometry and Photometry

The description and measurements of the propagation of the energy of the electromagnetic waves radiated by light sources uses twofold approaches.
The so called radiometric (physical) approach is based on the entire radiant power produced by the source while the photometric (physophysical) refers only to the part of the radiant power perceived by the human eye as light and human average response function. The spectrum of radiant energy waves that we call light is narrow, ranging from approximately 300nm to 750nm. Wavelengths shorter (UltraViolet) or longer (InfraRed) than these do not produce the visual response in the eye.

Consequently we have two set of quantities and units used in measurements – see table 1. The symbols for radiometric quantities are analogous to the photometric counterpart.

All photometric quantities can be obtained from the corresponding radiometric quantities on the basis of the spectral luminous efficacy human eye response

The relationship between the (physical) radiometric and the (psychophysical) photometric set units is established by the chosen value of spectral luminous efficacy for human vision: 683 lumens/watt.

In both approaches the basic concepts are similar and describe:

Power of the source

The light source is characterized by the total light output of a light source - total power radiated by it [in watts]. This is called **Radiant power** or **Radiant flux Φ**. In radiometry the unit of **Φ** is **watt [W]**. When referred to the sensitivity of the human eye and so called optical part of the radiated spectrum it determines the Luminous flux (or luminous power). The photometric unit of **Φ** is **lumen [lm].**

Intensity

The commonly used term intensity of light ("brightness") refers to the energy radiated by the source into the unit solid angle in a unit time. This power per unit solid angle is called **Radiant intensity *I*** in watts/steradian. The photometric unit of the intensity (**pointance, luminous intensity**) is candela [cd]. The **radiant intensity** enables to describe spatial characteristics of the source. In general, it is given by: $I(\Omega) = d\Phi/d\Omega$.

Illumination

In everyday life our visual reception is based on the effect produced by the light source at the surface of the surrounding objects. This means that we are interested in the amount of radiated energy, which reaches the observed surface element in a unit time. The **irradiance E** expresses radiation power (flux) received by the unit area of the illuminated surface. The unit of irradiance is **watt/m^2**. The respective photometric term is called **illuminance** and is given in **lux = lumen/m^2**.

The irradiance (as well as the illuminance) of a surface due the point light source depends on the radiant intensity, the distance to the surface, and the orientation of the surface with respect to the source:

$$E = \frac{radiant\ flux\ \Phi}{area\ A} = \frac{I \cdot \Omega}{A} = \frac{I \cdot A}{A \cdot r^2} = \frac{I}{r^2} \qquad (1)$$

where flux in a defined solid angle is :

$$\Phi = I \cdot \Omega \qquad (2)$$

and solid angle:

$$\Omega = \frac{A}{r^2} \qquad (3)$$

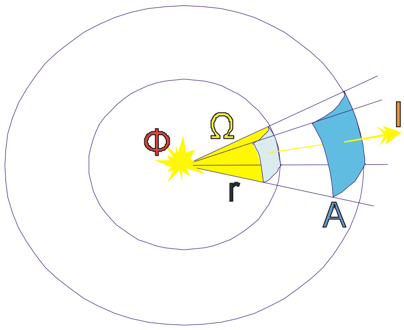

Fig.1. Radiant flux ***Φ*** and radiant intensity ***I***

Solid Angle:

The solid angle **Ω** refers to the cone cut out from the sphere. Solid angle is related to the area A intercepted by the cone on the surface of a sphere of radius r centered on the cone vertex: A/r^2
The unit of the solid angle is **steradian [sr]**.

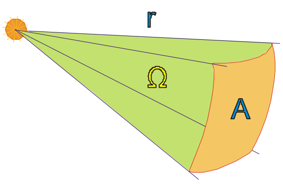

Fig.2. Solid angle

For the surfaces not perpendicular to the direction of light propagation the illumination expression E should be modified in order to deal with the effective (projected) area of the illuminated surface – see the fig.(1):

$$E = \frac{I}{r^2}\cos\phi \qquad (4)$$

where φ is the angle between the normal to the surface and direction of the propagation of the light energy.

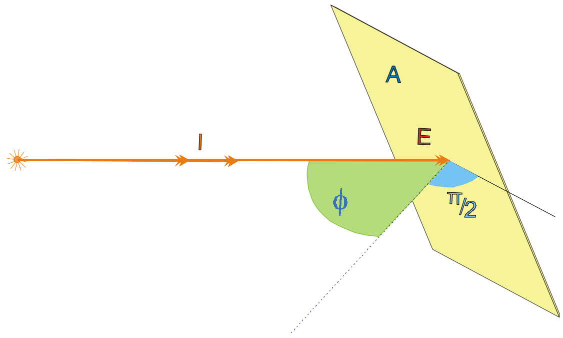

Fig. 3. Irradiance ***E*** at the inclined plane

The inverse square law.

The illumination produced by the point light source, which radiates equally in all directions follows the so-called Inverse square law.
It expresses the fact that amount of energy that passes through the unit area drops with the distance from the source. The total power irradiated by of the source (radiant flux) in all directions (into the full solid angle) remains constant while the total area of the sphere increases with the square of the radius.

$$E \cong \frac{I}{r^2} \qquad (5)$$

So, the power per unit area drops – compare fig. 1. The general character of the inverse square law applies to many other phenomena based on point sources e.g. gravity pf point masses, electrostatic field of point charges etc.

Table 1. Radiometric and photometric quantities.

Radiometry			Photometry		
Quantity	**symbol**	**units**	**units**	**symbol**	**Quantity**
Radiant Energy	*Q*	J	lm s	*Q*	Luminous energy
Radiant Flux	Φ	W	lm	Φ	Luminous Flux
Irradiance	*E*	W/m^2	lm/m^2	*E*	Illuminance
Radiant Intensity	*I*	W/sr	lm/sr	*I*	Luminous Intensity
Radiance	*L*	$W/(m^2\ sr)$	$lm/(m^2\ sr)$	*L*	Luminance

B. Absorption of light by the set of transparent plates.

Light passing through an optical system is attenuated by absorption of the transparent material and reflection at the interfaces.
Absorption means reduction of the radiant intensity ***I***, and results from many different phenomena. Part of radiated energy transfers into the heat while electromagnetic wave interacts with molecules of the medium.
The lose of energy depends on the pathlength of light in the medium, properties of the material and on the light wavelength (and to less extend on the external factors such as temperature). Impurities and structural defects may result in scattering, which reduces the effective radiant intensity leaving the sample of the transparent material.
There are different ways of describing the attenuation of the light by medium and several terms are used in order to describe the absorbing properties such as absorption coefficient, absorbance, absorptivity, and transmittance.
The absorption is described by the empirical expression called **Beer-Lambert law**, also known as **Beer's law** or the **Beer-Lambert-Bouguer law.**

For solids the Beer-Lambert law states that for a parallel beam of monochromatic radiation passing through a homogeneous material the lose of radiant intensity $-\Delta I$ is proportional to the product of pathlength through the material Δx and the initial radiant intensity- Fig.4.

$$-\Delta I = I\tau\Delta x \quad (6)$$

where τ is called the absorption coefficient and represents the relative lose of radiant intensity per unit pathlength in the material. Its unit [m^{-1}].

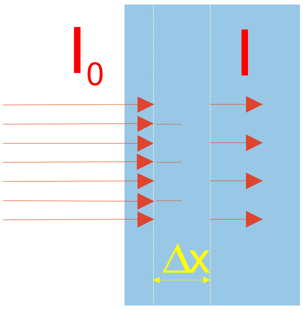

Fig.4. Attenuation of the light by the material

Absorption coefficient for the certain material is dependent on the wavelength of light, which results in many interesting and common phenomena (such as coloring). In case of liquid solutions the coefficient value depends additionally on the solvent and concentration.

Expression () leads to the more common form of the same statement known as exponential law of absorption.

$$I = I_0 e^{-\tau x} \quad (7)$$

Which describes the outgoing radiant intensity ***I*** after traveling along the pathlength ***x*** in the material. I_0 expresses the intensity of the light entering the sample. Equation (7) expresses the so-called **Beer-Lambert** law for transparent solid material. Fig.5. shows typical absorption curve.

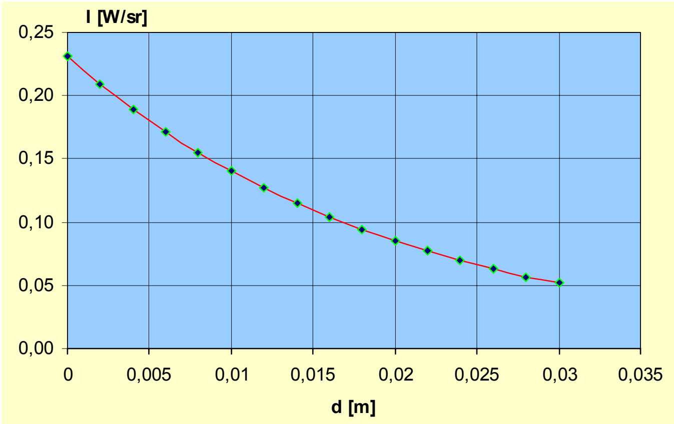

Fig.5. Intensity vs thickness. Exponential absorption.

Typically light beam enters the sample of the transparent material incoming from another medium (with different index of refraction). When light passes the interface it is subjected to the reflection from the boundary see Fg.6.

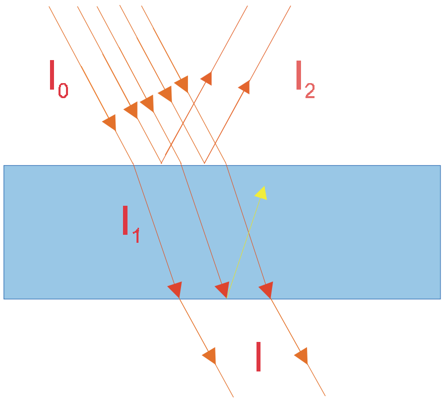

Fig.6. Parallel plate. Absorption and reflection.

Intensity of the reflected beam is given by:

$$I_2 = I_0\left(\frac{n-1}{n+1}\right)^2 \qquad (8)$$

Term ***[(n-1)/(n+1)]²* = *R*** is called the reflection coefficient (defined for pair of media and independent on the direction of propagation)

$$R = \left(\frac{n-1}{n+1}\right)^2 \qquad (9)$$

Where ***n*** – is the relative index of refraction of the reflecting medium.

So, the effective radiant intensity which enters the absorbing medium is already reduced by some factor and is given by:

$$I_1 = I_0(1-R) \qquad (10)$$

Similarly light leaving the sample partially reflects back at the second interface. Eventually, the radiant intensity I effectively leaving the sample is affected by absorption and two reflections (compare Fig.5.):

$$I = I_0(1-R)^2 e^{-\tau x} \qquad (11)$$

Note. The equation (11) does not take into account secondary (multiple) reflections from the boundaries. However, the error made due to that fact is small - of the order of 0.2%.

In case of stack of ***k*** transparent plates of equal unit thickness ***d*** the outgoing intensity is given by:

$$I = I_0(1-R)^{2k} \cdot e^{-\tau kd} \qquad (12)$$

The form above equation is not convenient in purpose of finding the coefficient of absorption via the experiment.

One can find that logarithmic form of it expresses the linear dependence of the radiant intensity versus number of plates ***k:***

$$\ln I = \ln I_0 + k \cdot [2\ln(1-R) - \tau d] \qquad (13)$$

So, the absorption coefficient can be found from the slope ***a*** of the ***lnI(k)*** curve.

$$\tau = \frac{1}{d}[2\ln(1-R) - a] \qquad (14)$$

Therefore from observation of outgoing intensity as a function of increasing number of transparent plates one can establish the absorption factor of the material.
The absorption coefficient is dependent on the wavelength of the light. In the present experiment the semi white light produced by the standard incandescent lamp is used. So, one can speak about the effective average absorption coefficient in this case.

APPARATUS FOR THE EXPERIMENTAL EXPLORATION.

Observation of the attenuation by a set of transparent plates can be performed using the simple setup consisting of standard lamp handle placed on the optical bench with glass plates holder and adjustable light detector see fig. 7
The light sensor uses a phototransistor with an active area positioned at a fixed distance from a light source. The detector measures relative irradiance ***E***. The units of irradiance are milliwatts per square centimeter. The light sensor's output is a voltage that is linearly proportional to the amount of irradiance it senses. The light is subject to the absorption by the material and reflection at each interface encountered.
This configuration assumes a point source, therefore the inverse square law holds true.

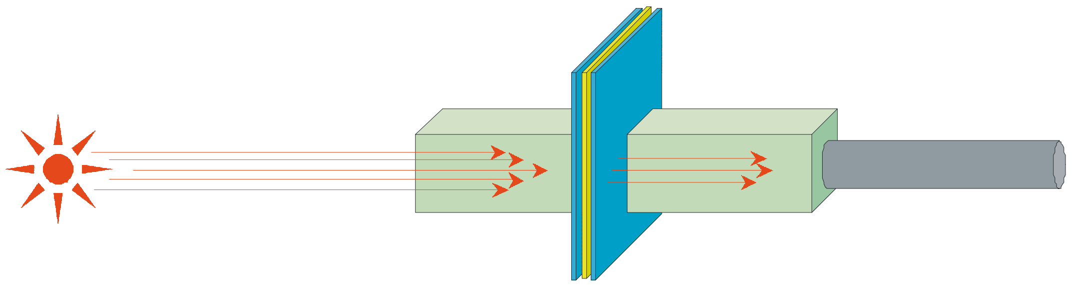

Fig.7. Diagram of the experimental setup

Experiment uses:

i. goniometer with the glass plates holder.
ii. lamp housing E14
iii. incandescent lamp (e.g. 15 - 40W)
iv. set of parallel glass plates of equal thickness e.g. base glass used for microscopic observation (***d=1.6mm)***. The index of refraction ***n*** of the glass is assumed to be ***n=1.5***.
v. Calculator Based Laboratory unit CBL
http://www.vernier.com/legacy/cbl/index.html
or CBL2
http://education.ti.com/us/product/tech/datacollection/features/cbl2.html
vi. Light probe (standard CBL or Vernier's LS BTA)
http://www.vernier.com/probes/probes.html?ls-bta&template=standard.html
vii. Graphic calculator TI83, TI83 Plus, TI 83 Plus SE.
viii. unit-to unit cable (standard).
ix. Program: PHOT3,– available for download at: http://www.lepla.edu.pl/
x. TI-GRAPH LINK ™ (optional) cable
http://education.ti.com/us/product/accessory/connectivity/features/cables.html#serialwin
and software
http://education.ti.com/us/product/accessory/connectivity/down/downgraph.html
xi. Personal computer with TI Connect™ software (optional)
Description:
http://education.ti.com/us/product/accessory/connectivity/features/software.html
Download:
http://education.ti.com/us/product/accessory/connectivity/down/download.html

Practical notes about the apparatus setup.

- The Light probe should be connected to the channel CH1 of the CBL unit.
- Examined glass plates should be slightly separated from each other by thin (1mm) spacers.
- One should adjust the height of the detector's mount with the center of the light source.
- The ambient light should be reduced and kept stable during the experimental session.

DATA ACQUISITION (TI 83)

In the experiment the light sensor measures relative irradiance ***E*** in milliwatts per square centimeter as a function of the number ***k*** of the transparent plates of equal thickness ***d*** introduced manually into the light path.
Data will be presented in the rectangular coordinates as the E(kd) plot. The experiment is controlled by means of the preloaded calculator program PHOT3.

Experimental procedure is divided into the preparatory part and the data acquisition.

Preparation:

Connect the light probe with the CBL and the CBL with the calculator.
Turn on the calculator and the CBL.
Measure thickness of the base glass plates. Work out the average value ***d***.

Measuring the ambient light should precede the main measurements. So, reduce it and make sure that it will not change during data collection.

1. Launch the program PHOT3 by choosing its name from the PRGM menu.
2. Choose ZERO PROBE from the program menu – Fig.8.
3. Keep the light source off and remove all plates from the holder. Start collecting data – Fig.9.

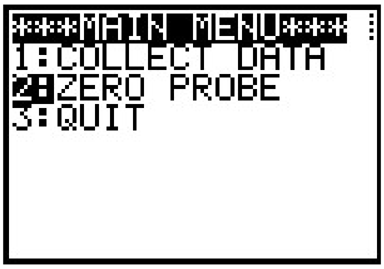

Fig.8. Fig.9.

The collected irradiance value will be subtracted from any other collected irradiance data.

The described calibration is to be done once during the experimental session providing that the ambient illumination does not change.

Data collection

1. Choose option 1: COLLECT DATA from the main menu.
2. Introduce the average plate thickness ***d*** (in meters!) when prompted – Fig.10.
3. Turn on the light source.
4. Start collecting data when ready. – Fig.11. Note that the first data point should be collected without the plates in the lightpath.
5. Introduce the number of plates when prompted (Fig.12).
6. Take another data point for different number of plates by choosing 1: MORE DATA option from the DATA COLLECTION menu – FIG.13.
7. Finish collecting data by choosing 2: STOP AND GRAPH.
8. Choose the plot type from the DATA PRESENTATION menu – Fig.14. Collected data can be presented either as the irradiance vs total thickness of the absorbing material (***kd***) or as the irradiance vs number of plates (***k)*** – Fig.15.
9. If you are not satisfied with he obtained data, repeat using the same or new settings (new calibration is not necessary).
10. Collected data are stored in a calculator's memory and you can proceed using the standard calculator's functions. Now you can disconnect the CBL from the calculator.

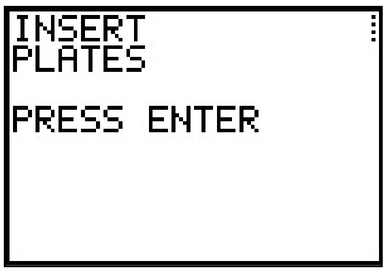

Fig.10. Fig.11.

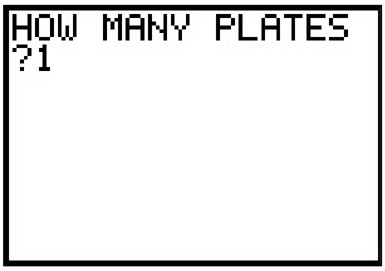

Fig. 12

Fig.13

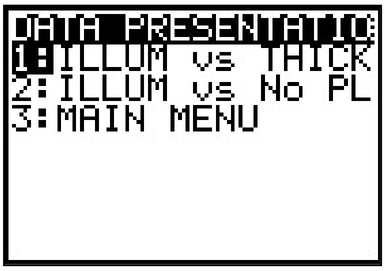

Fig.14

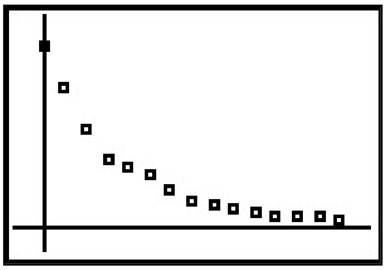

Fig.15.

Fig.16.

DATA ANALYSIS (TI83)

Further analysis can be performed using tools implemented in calculators (or other analytical software tools such as MS Excel spreadsheet).

Collected data are stored in the calculator's lists - Fig.16:
- total thickness of plates ***d*** in meters - List L_1
- irradiance ***E*** in watts/cm^2 - List L_2
- number of plates ***k*** – List L_3

Exemplary data are available for a download in the following calculator type files:

- total thickness of plates ***d*** in meters as the file - Data sample/TI83/ $\mathbf{L_2}$
- irradiance ***E*** in watts/cm^2 - Data sample/TI83/ $\mathbf{L_2}$
- number of plates ***k*** - Data sample/TI83/ $\mathbf{L_3}$
-

Experimental data plots are defined as Plot1 (L_2 vs. L_1) and Plot2 (L_2 vs. L_3) can be recalled by STAT PLOT menu.

Analysis of plots

Assuming fixed detector positioning with respect to the source the measured irradiance ***E*** dependence can be analysed as the respective radiant intensity ***I (kd)*** dependence and the exponential law of absorption.

Therefore analysis of the obtained data can be performed in terms of the equation eq.12. which combines effect of absorption with reflection:

$$I = I_0 (1 - R)^{2k} e^{-\tau kd} \qquad (12)$$

By analysis of the observed irradiance as function of increasing number of transparent plates one can establish the absorption coefficient τ of the material.

The original irradiance data should be transformed into the natural logarithms as the logarithmic form of eq. 12 expresses the linear dependence of the radiant intensity versus number of plates ***k***:

$$\ln I = \ln I_0 + k \cdot \left[2\ln(1-R) - \tau d \right] \qquad (13)$$

So, the absorption coefficient can be found from the slope ***a*** of the ***lnI (k)*** straight line.

$$\tau = \frac{1}{d}\left[2\ln(1-R) - a \right] \qquad (14)$$

Linearization

According to the eq.13. the ***E(k)*** plot should have a form of a straight line. In order to examine this the original irradiance data gathered in the list L_2 - ***E***, should be transformed to ***ln(E)*** The transformed data are stored in a new list L_4 – Fig.17.
Now, one the new plot should be defined as L_4 vs. L_3 and displayed – Fig. 18. The data points well match the straight line, so assumption of the linear dependence is justified and one can apply the linear regression model. The linear regression is recalled from the STAT CALC menu (Fig.19) with the respective arguments – Fig. 20. As the result the parameters of the linear function are calculated and the function is stored as the Y_1. The result of the regression is displayed – Fig. 21.
The correlation coefficient ***r*** expresses the quality of the approximation. In a given example the ***r*** value is close to 1, which confirms good linear correlation between logarithm of irradiance ***E*** and number of plates ***k***.
This can be seen as well in the combined plot of experimental data and regression line – Fig. 22.

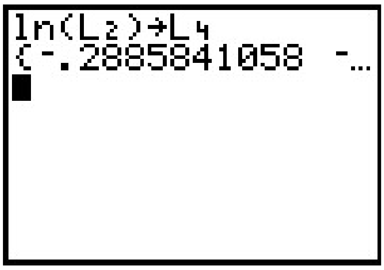

Fig.17

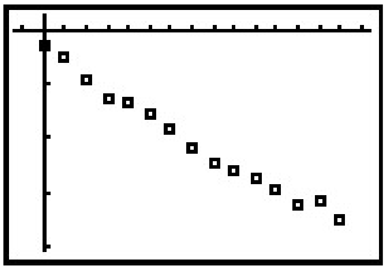

Fig.18

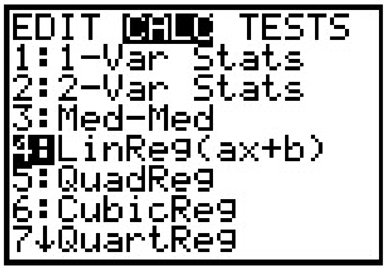

Fig.19

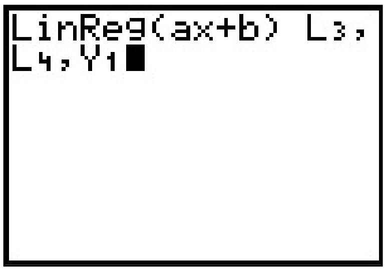

Fig.20

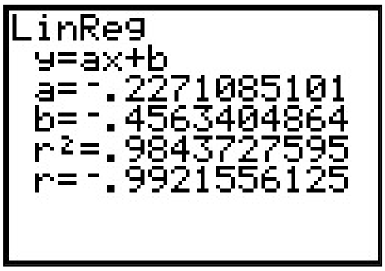

Fig.21

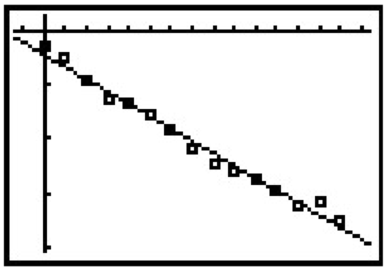

Fig.22

Calculation of the absorption coefficient

According to the eq. 14 one can calculate the coefficient τ from the slope ***a*** of the obtained regression line.
Firstly the reflection coefficient ***R*** *should* be evaluated from the eq. 9 and the refractive index ***n*** known value**.** The ***R*** value is stored in the constant – Fig.23.

Now the calculation of τ can be performed. Note: the single plate thickness ***d*** is already stored in the memory as ***D*** while the slope ***a*** value can be recalled from the VARS Statistics menu – Fig. 24. Eventually one obtains the absorption coefficient value (in [m^{-1}] – Fig. 25.

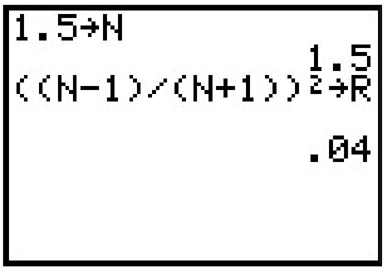

Fig.23

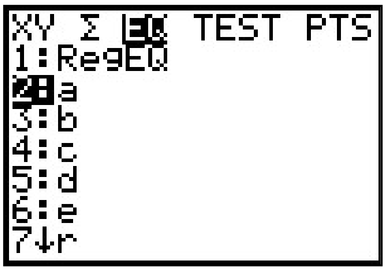

Fig.24

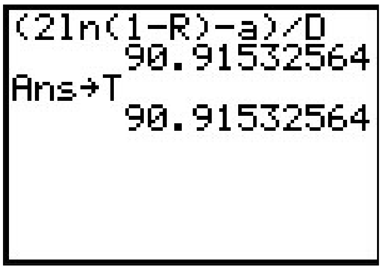

Fig.25

<u>DATA ANALYSIS (MS EXCEL)</u>

Analysis can be performed using tools implemented in calculators and personal computer functions offered by the MS Excel software.

Transfer of experimental data to the personal computer.

After completing the experiment data could be transferred from the graphic calculator to the personal computer.
TI GRAPH LINK™ cable supported by the TI Connect™ software offer tools enabling exploration of the contents of calculator (TI DEVICE EXPLORER) and data edition (TI DATA EDITOR).
Data collected in the experiment are stored in the calculator's lists:

- total thickness of plates ***d*** in meters - List L_1
- irradiance ***E*** in watts/cm^2 - List L_2
- number of plates ***k*** – List L_3

Within the TI Connect™ program - the TI DEVICE EXPLORER one can save calculator's lists on the computer's hard disk and then open them within TI DATA EDITOR. Option **Special Lists Export** provides opportunity to save the chosen list as the Excel Comma Separated type file (*CSV file). Such a file could be open and explore within the MS Excel™ spreadsheet software.

Exemplary data are available for a download in the following files:

- total thickness of plates ***d***: as file - Data sample/MSExcel /**thick**
- irradiance: as file - Data sample/MSExcel/**intensity**
- number of plates ***k*** as file: Data sample/MSExcel/**kplates**

Analysis of plots

Create a spreadsheet and import the data from the files **thick, kplates** and **intensity.** Make the plot E(d) from the experimental data. Choose scattered type of the plot – Fig. 26.

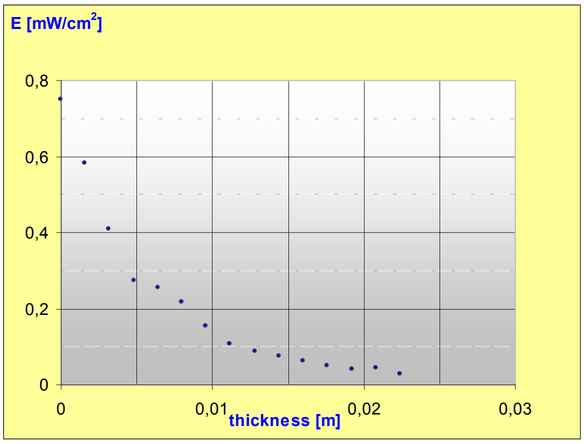

Fig. 26. Irradiance vs thickness of the absorbing plates

Assuming fixed detector positioning with respect to the source the measured irradiance ***E*** dependence can be analysed as the respective radiant intensity ***I (kd)*** dependence and the exponential law of absorption.

Therefore analysis of the obtained data can be performed in terms of the equation eq.12. which combines effect of absorption with reflection.

By analysis of the observed irradiance as function of increasing number of transparent plates one can establish the absorption coefficient τ of the material.

The original irradiance data should be transformed into the natural logarithms as the logarithmic form of eq. 12 expresses the linear dependence of the radiant intensity versus number of plates ***k***:

$$\ln I = \ln I_0 + k \cdot [2\ln(1-R) - \tau d] \qquad (13)$$

So, the absorption coefficient can be found from the slope ***a*** of the ***lnI (k)*** straight line.

$$\tau = \frac{1}{d}[2\ln(1-R) - a] \qquad (14)$$

Linearization

According to the eq.13. the ***E(k)*** plot should have a form of a straight line. In order to examine this the original irradiance data ***E*** should be transformed to ***ln(E)*** and stored in a separate column of the spreadsheet.
The new plot should be defined as ***ln(E) vs k*** and displayed – Fig. 27.

The data points well match the straight line, so assumption of the linear dependence is justified and one can apply the linear regression model by adding trend line (linear type) to the plot. The trend line is drawn and resulting linear expression is displayed in the plot – Fig. 27.The determination coefficient R^2 expresses the quality of the approximation. In a given example the R^2 value is close to 1, which confirms good linear correlation between irradiance ***E*** and ***k***.

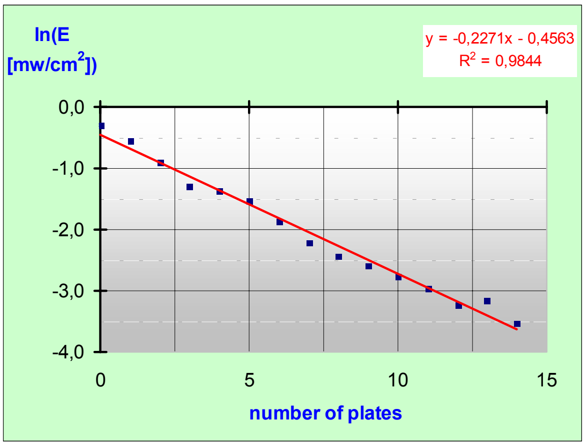

Fig. 27. Logarithmic plot of irradiance vs number of plates.

Calculation of the absorption coefficient

According to the eq. 14 one can calculate the coefficient τ from the slope ***a*** of the obtained regression line.
Firstly the reflection coefficient ***R*** should be evaluated from the eq. 9 and the refractive index ***n*** known value**.**

Eventually the calculation of the τ can be performed. The obtained absorption coefficient value is in $[m^{-1}]$ – Fig. 28.

CALCULATIONS		
index of refraction n =	**1,5**	
index of reflection R =	**0,04**	
slope of the lnE vs k line a =	**-0,2271**	
thickness of the single plate d	**0,0016**	**[m]**
coefficient of asborption τ =	**90,9100**	**$[m^{-1}]$**

Fig. 28. Calculation results

One can extend the discussion on the absorption of light by transparent materials by making measurements of the uniform single thick glass plate (possibly the same type of glass) and comparing plot with the plot for stack of thin plates of equivalent total thickness. The influence of reflections at the interfaces should be noticeable.

Note:

The complete numerical analysis is presented in the MSExcel file:
Data sample/MSExcel /absanalysis