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Problems related to the angular resolution of the ILMD for GR index determination

***Abstract**. The article presents problems of angular resolution of a photometer matrix (imaging luminance measurement device – ILMD) used for glare rating GR determination based on luminance distribution measurements. The analysis was carried out, how the various measured parameters influence on the uncertainty of the GR index determination. Analysis and conducted experiments showed that in specific cases the impact of angular resolution on the result of the GR is completely negligible.*

***Streszczenie.** W artykule przedstawiono problemy rozdzielczości kątowej fotometru matrycowego przy wyznaczaniu wskaźnika olśnienia GR na podstawie pomiaru rozkładu luminancji. Przeprowadzono analizę wpływu poszczególnych mierzonych parametrów na niepewność wyznaczania wskaźnika olśnienia GR. Analiza oraz przeprowadzone eksperymenty pokazały, że w szczególnych przypadkach wpływ rozdzielczości kątowej matrycy na wynik GR jest całkowicie pomijalny. (**Problemy rozdzielczości kątowej miernika matrycowego przy wyznaczaniu wskaźnika olśnienia GR**).*

Keywords: GR index, ILMD, matrix angular resolution
Słowa kluczowe: wskaźnik olśnienia GR, matrycowy miernik luminancji, rozdzielczość kątowa matrycy

Introduction

Glare phenomenon is caused by the appearance of light sources of a very high luminance in the field of view. It occurs both on: the indoor and outdoor workplaces. It can cause different effects depending on the geometric and photometric parameters of a lighting system. Discomfort glare is the sensation of annoyance, while disability glare is the reduction in visibility caused by intense light sources in the field of view for a short but noticeable time. Glare limitation to a level appropriate to the visual task difficulty is an important measure of lighting quality. Unfortunately, glare as the lighting quality parameter may not always be assessed in an objective way in the working environment, although there are standardized requirements for it [1, 2].

In conditions of exposure to glare on the outdoor workplaces can work approx. 3.7% of the total employment in the national economy in Poland. Poor visibility due to glare is considered as one of the indirect reasons of the occupational accidents, in particular at outdoor workplaces when work is carried out after twilight. Our study [3], including an analysis of the occupational accidents as well as numerous expert opinions in workplaces showed that such incidents are often not reported in the statistics. To a large extent the irregularity corresponds to the lack of adequate knowledge and measurements methods for the evaluation of discomfort glare at the workplaces. A numerical measure used to determine the degree of discomfort glare on indoor workplaces is UGR index [1, 4]. On outdoor workplaces it is GR index [2, 5, 6, 7]. Both indexes depend on a luminance of glare sources (or veiling luminance by the glare source) and on a luminance of the background / environment (veiling luminance by the environment). In both cases the background luminance (veiling luminance by the environment) can be determined based on the illuminance measurements. The glare source position in relation to observation line is also taken into consideration, but in a different way for both indexes.

Lighting design of the working environment should include the calculation of the relevant glare index. This index should be verified after the installation of the lighting equipment. The most reliable verification of calculated glare index is that which can be carried out based on measurements in the real workplace environment.

Verification by measurement of UGR index (except for LED sources) is currently possible but it hasn't been possible for GR index until now.

One of the basic problems, which makes difficult determination of the glare indexes, is taking into account the geometrical relations between parameters and the angular resolution of the equipment used for the luminance measurement. Distant location of the luminaires from the observer makes angular dimensions of the light sources very small. Therefore, the selection of appropriate optical system for GR measurements is important. Two important measurement aspects must be provided: the proper angular resolution of an array photometer and the large enough photometer field of view. The article presents the analysis of the main angular relations associated with photometer's optical system which are necessary to take into consideration for GR measurement.

Glare index for the outdoor workplaces

The principles for glare assessment on outdoor workplaces are described in CIE publications [6, 7] and in European Standard EN 12464-2 [2]. GR index, which describes the level of glare is based on the formula (1) [2, 6, 7].

$$GR = 27 + 24 log_{10}\left(\frac{L_{vl}}{L_{ve}^{\;0.9}}\right) \quad (1)$$

where: L_{vl} – the veiling luminance (cd/m^2) caused by the lighting installation, it can be calculated by the formula (2) as the sum of the veiling luminances produced by each individual luminaire L_{vi} . L_{ve} – the equivalent veiling luminance of the environment (cd/m^2), determined from formula (6) or (7).

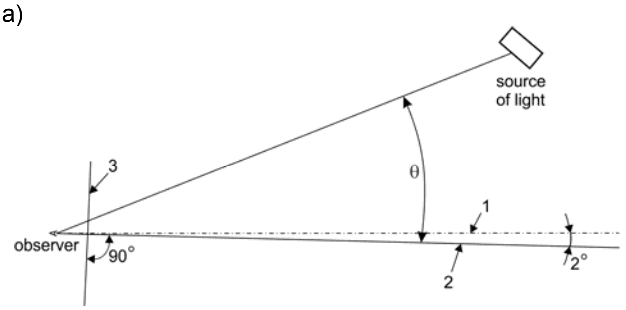
$$L_{vl} = L_{v1} + L_{v2} + ... + L_{vn} \quad (2)$$

The veiling luminance of the individual luminaire L_{vi} is calculated by (3).

$$L_{vi} = 10 \cdot E_{eyei} \cdot \theta_i^{-2} \quad (3)$$

where: E_{eyei} – the illuminance at the observer's eye in a plane perpendicular to the line of sight (2˚ below the horizon – Fig. 1.) from the individual luminaire. θ_i – the angle between the observer's line of sight and the direction to the individual luminaire. CIE publication [6] and standard [2] define this angle to be in range between 1.5° and 60°. The angle θ is defined according to Figure 1. [2, 7]. This angle in formula (3) is expressed in degrees [6, 8].

a)



b)

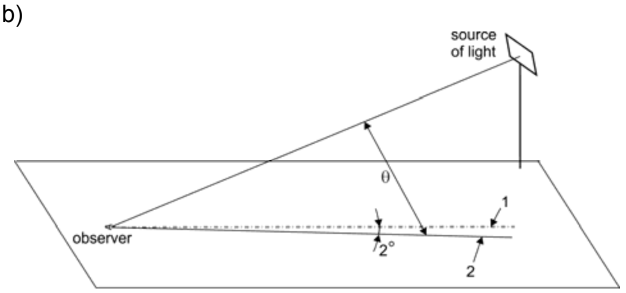


Fig.1. Definition of the angle θ : 1 – the horizontal line, 2 – the line of sight (2° below the horizontal line), 3 – the plane of E_{eye} perpendicular to the line of sight, a) the cross section of the field of view [2], b) the spatial arrangement [7]

The illuminance at the observer's eye from the individual luminaire can be determined by formula (4) [9]:

(4) $$E_{eyei} = L_{ai} \cdot \omega_i \cdot cos\,\theta_i$$

where: L_{ai} – the average luminance of the individual luminaire i, ω_i – the solid angle in which this luminaire is seen.
The application of modern matrix luminance meter allows to determine the luminance map of the luminaire (source of glare). In this case the formula (4) takes the form (5):

(5) $$E_{eyei} = \sum_j L_{ij} \cdot \omega_{ij} \cdot cos\,\theta_{ij}$$

where: L_{ij} – the luminance which corresponds to the luminance of a single measuring element j in the luminance map of the luminaire i, ω_{ij} , θ_{ij} – the angles which correspond to a single measuring element j in the luminance map of the luminaire i .

Assuming that the reflections from the environment are completely scattered, the equivalent veiling luminance of environment (L_{ve}) can be calculated from the formula (6) [2].

(6) $$L_{ve} = 0.035\rho \cdot E_{hav} \cdot \pi^{-1}$$

where: ρ – the average reflectance of the area, E_{hav} – the average horizontal illuminance of the area.

The different formula (7) for the equivalent veiling luminance of environment can be also found in the literature [10].

(7) $$L_{ve} = 0.035 \cdot L_b$$

where: L_b – the average luminance of the environment.

Formula (7) used to evaluate the GR does not limit the applicability of this index to the surface, which is characterized by diffuse reflection. It allows determining the average luminance of the background based on the measurement of the luminance distribution (using matrix photometer) for each type of surface (not only totally diffuse environment) . Determination of the veiling luminance of the environment in this way gives the opportunity to take into account any shape and size of the surface forming the background for the glare source in the workplace. Measurement of luminance is the only way to take into consideration these parameters.

The geometrical limitations and the problem of small light sources

A major problem in assessing the glare is the luminance measurement of small light sources. Initially, this problem has appeared on the assessment of the glare from louver luminaires. Currently, this problem is particularly important due to the rapid increase in the use of LEDs for lighting. They have a very small angular sizes and very high values of the luminance at level of $10^5 \div 10^8$ cd/m^2. According to CIE document [11] light sources are considered as small if they are seen by an observer at an angle less than 0.0003 sr and the UGR can't be determined using glare source luminance. In this case, the luminance should be expressed as the quotient of the luminous intensity in the direction of the observer's eyes and the projected area of the luminaire (the field of apparent luminous surface). However, the use of this model also has its limitations. The apparent surface area of emitting sources should not be less than 0.005 m^2 (equivalent to a circular area with a diameter of approx. 8 cm), and the light source should be at least 5° above the line of sight. Unfortunately, the apparent surfaces of emitting LEDs are much smaller than 0.005 m^2 and this formula cannot be applied in this case. On the other hand, there are no restrictions related to the viewing angle of glare sources for GR index determination on the outdoor workplaces.

The introduction of matrix luminance meters – imaging luminance measurement device (ILMD) has revolutionized the approach to the glare assessment at workplaces. Indeed it allowed determining the luminance distribution in real conditions, not only at the design stage of lighting. We used LMK photometer [12], as an example of such device in our experiments. However, the measuring properties of such devices have proved to be decisive limitations in the case of very small light sources and sources with a non-uniform distribution of luminance. The angular resolution of the matrix in ILMD is the very important parameter in this case. This is the parameter that determines the measurement capability of small light sources [13].

Analysis of the resolution problem demonstrates the inability to measure the luminance of sources with specific (small) angular size. If the size is comparable to the size of a single measuring element (pixel) of ILMD, then it will cause a huge measurement error. In such situation the correct recording of luminance of the light source is very difficult or impossible [13]. This applies to a very small size of the light source and of the non-uniform luminance distribution (e.g. louvre luminaires), and especially to LEDs.

It is worth noting that the current discussion in literature, concerned only problem how the resolution impact on the measurement of the luminance distribution. But the problem of the influence of this parameter on the glare determination from the measured luminance distribution hasn't been discussed yet. It seems that the lack of opportunity to make the correct measurement of the luminance distribution makes it impossible to reliably determine the value of the glare index; however it is worth to have a closer look at this problem.

Analysis of the measurement uncertainties

Considering the equations (1), (3), (4) and (7) we can specify the formula (8), which allows to determine the GR index for a single glare source (for individual luminaire) taking into account all the parameters that can be measured.

(8) $$GR = 27 + 24\log_{10}\left(\frac{10 \cdot L_{ai} \cdot \omega_i \cdot \cos\theta_i \cdot \theta_i^{-2}}{(0.035 \cdot L_b)^{0.9}}\right)$$

In the case of determining the GR index we have to deal with the indirect measurements. To calculate the uncertainty of GR determination, the analysis of the measurement uncertainties for every quantity directly measured should be done. Formula (8) was analyzed by total differential and it allows obtaining the maximum absolute uncertainty of GR (9), (10).

(9) $$\Delta_{GR} \le \left|\frac{24}{\ln(10) \cdot L_{ai}}\right| \cdot \Delta_{Lai} + \left|\frac{24}{\ln(10) \cdot \omega_i}\right| \cdot \Delta_{\omega i} + \left|\frac{-24 \cdot (\theta_i \cdot \tan(\theta_i) + 2)}{\ln(10) \cdot \theta_i}\right| \cdot \Delta_{\theta i} + \left|\frac{-24 \cdot 0.9}{\ln(10) \cdot L_b}\right| \cdot \Delta_{Lb}$$

i.e.

(10) $$\Delta_{GR} \le \frac{24}{\ln(10)}\left(\frac{1}{L_{ai}} \cdot \Delta_{Lai} + \frac{1}{\omega_i} \cdot \Delta_{\omega i} + \left(\tan\theta_i + \frac{2}{\theta_i}\right) \cdot \Delta_{\theta i} + \frac{0.9}{L_b} \cdot \Delta_{Lb}\right)$$

where: Δ_{GR} – the uncertainty of GR measurement (indirect), Δ_{Lai} – the uncertainty of luminance measurement for individual luminaire, $\Delta_{\omega i}$ – the uncertainty of solid angle ω_i measurement , $\Delta_{\theta i}$ – the uncertainty of angle θ_i measurement, Δ_{Lb} – the uncertainty of the average luminance of environment measurement.

Usually the average luminance of outdoor environment does not exceed 100 cd/m^2. Discomfort glare occurs at minimum value of source luminance about 500 - 700 cd/m^2 [14]. In practice, luminance value of individual luminaire is at least 1000 times greater than the average luminance of the environment (in the case of LEDs the luminances quotient may be even higher). In both of these cases, the luminance is measured by the same instrument, which means that the values of Δ_{Lai} and Δ_{Lb} are identical. On the basis of the formula (10), we can calculate the impact of measured luminance on the uncertainty of determined GR index. Considering the relationship between the luminance values of the light sources and environment, it is clear that the deciding factor is the uncertainty of measurement of the environment luminance. The impact of the uncertainty of measurement of luminaire's luminance is significantly smaller - practically negligible. On the other hand, we know that the lower or not sufficient resolution of the matrix photometer (ILMD) leads to a significant falsification of the results [13]. This applies to averaging of luminance values from larger areas of measurement. But concerning to formula (7), determining of L_{ve} luminance applies precisely the averaging value of the environment luminance. Thus, even a relatively larger local changes in luminance, if not interpreted correctly by the appropriate resolution, they will be simply averaged at a single measuring element of the matrix. In that case, it is difficult to say that the measurement resolution significantly influences the determination of the equivalent veiling luminance of the environment.

Much more important is the problem of providing adequate resolution of ILMD to measure the luminance of the light sources. However, in this case, it is worth paying attention to quantities and dependencies used to determine the veiling luminance L_{vl} – formulas (2-4). If we consider changing the position of the source, while preserving the same angle θ and source luminance, the decisive parameter becomes the solid angle ω in which the source is seen. It is very important because the solid angle of a light source decreases proportionally to the square of the distance. In this case, the influence of this source on the GR index decreases in the same way.

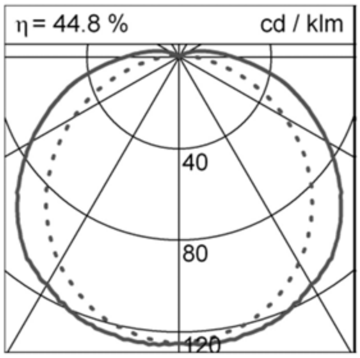


Fig. 2. The curves of luminous intensity for fluorescent luminaire with frosted and textured glass diffuser, used in experimental studies [15]

The experiments and simulations

In order to confirm the theoretical considerations for uncertainty of GR we conducted experiments including simulation in DIALux and measurement of the luminance distribution. The measurements were carried out in the laboratory of size 4.3 m by 8.6 m. We used fluorescent luminaire with frosted and textured glass diffuser (Maxi, manufactured by RZB Rudolf Zimmermann) 1x36 W [15], as a glare source (the curves of luminous intensity in planes C0 and C90 are presented in Figure 2.). The luminaire was placed on a stand 1 m from the shorter wall and 1 m from the longitudinal symmetry axis of the room. The luminous center of the luminaire was at height of 2 m – it corresponds to DIALux height of mounting 2.130 m. The longitudinal axis of the luminaire was parallel to the shorter wall of the room. The LMK photometer was placed on the stand at a height 1.5 m, in such a way that the direction of view of the photometer was consistent with the longitudinal symmetry axis of the room (viewing direction: 0°), distance to the longitudinal axis of the luminaire was 4 m. Settings of the light source (**A**) and the LMK photometer (**L**) are shown in Figure 3.a). The luminance map registered by LMK photometer is presented in Figure 4.

Three different simulation using DIALux software were done. Using the known photometric data of the luminaire and geometric parameters (appropriate distances and angles), we can consider a hypothetical cases for rooms with larger dimensions (Case 1, 2, 3). It can be assumed that the position of **A** in relation to the photometer **L** is preserved in every simulations.

In the first simulation (Case 1, in Figure 3.b) geometric parameters and relation between the glare source (**A**) and LMK photometer were adopted in accordance with conditions in the laboratory. The GR index was calculated by DIALux simulation. GR = 58 in this case.

On the basis of the luminance map (Fig. 4.b.) angle ω was determined, in which the source of glare was seen. The source of glare was located in a rectangle of 132 x 47 pixels which corresponds to the solid angle ca $12.4 \cdot 10^{-4}$ sr (0.00124 sr).

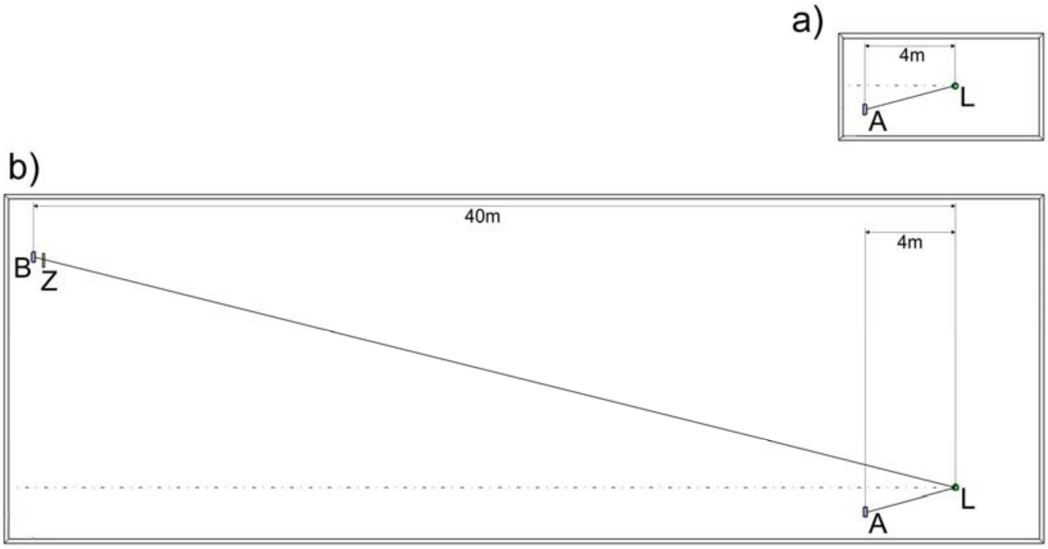


Fig. 3. The arrangement of: light sources (**A** and **B**), the opaque shield (**Z**) and the LMK photometer (**L**). In the experiment and simulations we used: a) in the laboratory: L + A , b) in DIALux simulation: Case 1: L + A, Case 2: L + A + B, Case 3: L + A + B + Z.

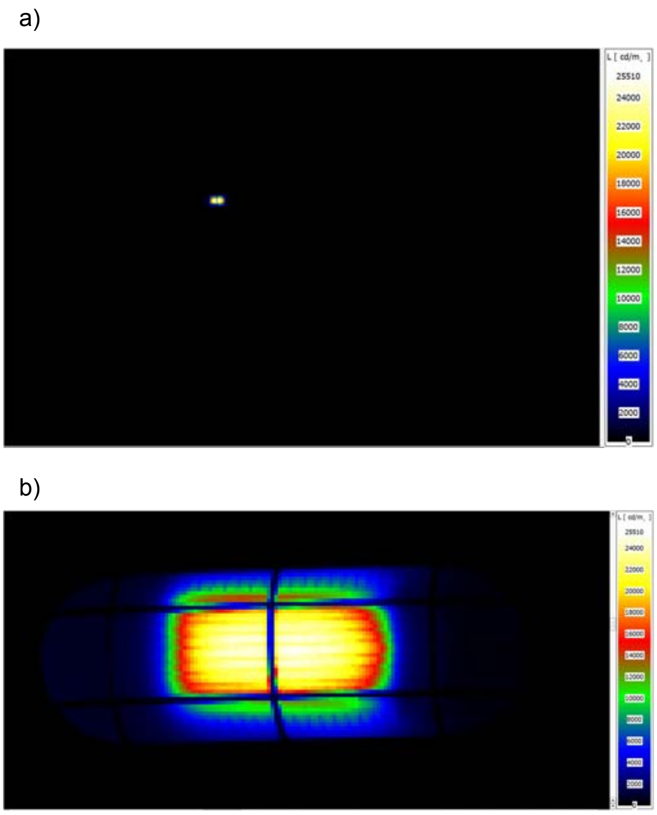


Fig.4. a) The map of luminance determined by LMK photometer in laboratory, b) enlarged fragment containing the source of glare. The maximum luminance of the source 25 510 cd/m^2

In the second and third simulations (Case 2, Case 3 in Figures 3.b) we assumed that the position of source of glare **A** in relation to the photometer **L** is preserved. In addition, let it be placed the second, identical luminaire (**B**) at a distance of 40 m from the photometer (Fig. 3.b). Let the angle θ between the vector to the source and the direction of view of the photometer be identical for both luminaires. Let the direction of glare source in relation to the walls of room be also the same for both luminaires (**A** and **B**).

Two different sources of glare exist in the hypothetical cases (Case 2 and Case 3):

- **A** – measured in real conditions and simulated in DIALux, measured parameters: the maximum of luminance L_{Amax} = 25 510 cd/m^2, the solid angle in which is seen from LMK photometer (and DIALux GR observer) $\omega_A \approx$ 12.4·10^{-4} sr (0.00124 sr),
- **B** – the maximum of luminance L_{Bmax} = 25 510 cd/m^2, the solid angle in which is seen from the DIALux GR observer $\omega_B \approx$ 12.4·10^{-6} sr (0,0000124 sr).

To determine glare from both sources **A** and **B** the maximum value of the luminance of the entire solid angle at which the luminaire is perceived can be established. This will estimate the maximum glare which may be caused in these conditions. The distance from photometer to the luminaire **B** is ten times larger than the distance to luminaire **A**. So the source **B** is seen in the solid angle 100 times smaller. It means that the whole source **B** can be located in a rectangle of 13 x 5 pixels, in the map of luminance. Such resolution does not allow performing correct luminance measurement of this source. This measurement may be affected by a huge error [13].

The short analysis can be conducted using all discussed parameters for the hypothetical cases. On the base of formulas (3) and (4) the veiling luminances can be calculated for sources **A** and **B**. Those luminances are described by (11) and (12).

(11) $$L_{vA} = 10 \cdot L_{A\,max} \cdot \omega_A \cdot \cos\theta_A \cdot \theta_A^{-2}$$

(12) $$L_{vB} = 10 \cdot L_{B\,max} \cdot \omega_B \cdot \cos\theta_B \cdot \theta_B^{-2}$$

But $L_{B\,max} = L_{A\,max}$, $\theta_B = \theta_A$ and $\omega_B = \omega_A / 100$. In that case $L_{vB} = L_{vA}/100$. And since, according to (2) $L_{vl} = L_{vA} + L_{vB} = L_{vA} + L_{vA}/100$, so after adding the source **B** the veiling luminance caused by the lighting installation has increased in this case, precisely, by 1%.

The second simulation in DIALux was carried out for Case 2 (Fig. 3.b). Both sources **A** and **B** were taken into account. The calculated glare index was: GR = 56. It is a smaller value than in Case 1 in the first simulation (GR = 58), although the veiling luminance increased. However, the addition of the light source **B** is associated with an additional lighting of the environment. In this way the equivalent veiling luminance of the environment increased and this caused a decrease of the GR index.

The third simulation in DIALux was carried out for Case 3. Both sources **A** and **B** were taken into consideration. Additionally the small opaque shield (**Z**) was placed between source **B** and photometer **L**. The size of the shield was chosen in such a way as to cover only the source and not the surrounding areas. The GR index was calculated by DIALux simulation. GR = 56 in this case. So the value of GR was exactly the same as in the Second Simulation although the source of glare **B** was covered.

The effects of simulation carried out in DIALux can be compared. Adding a second source of glare, which is seen in the relatively very small angle, can affect the veiling luminance of the environment, what can cause a decrease of the GR index. However, the impact on the veiling luminance from the lighting installation is very small. In addition, even covering such source and therefore not to take it into account in determining the veiling luminance from the lighting installation does not change the index GR. In such a situation, when measuring the luminance of the source **B**, making a huge error (up to 100%) practically changes nothing.

Summary

In the article the measurement of the light sources luminance, using a matrix photometer (ILMD) was considered. Analysis of the problem how the resolution of such measurement affects the value of the GR index was presented. The authors of publications concerning the problems of using ILMD in glare analysis always emphasize that there is no possibility to measure the light source luminance from a long distance in accurate way. This is caused by insufficient resolution of the photometer and is associated with a huge error of averaging.

However, the analysis of uncertainty of the glare index determination and considered in this article examples show that it is worthwhile to look at the resolution problem from the other side. It is worth to consider the consequences of other parameters changes – especially the solid angle in which the source of glare is seen. Additionally it is worth to analyze the dependencies between parameters what result directly from the formulas used in glare determination. In the discussed examples, the impact of the problem of measurement resolution and the associated huge luminance measurement error is negligible.

On the other hand, attention should be paid to the fact that the conclusions presented here cannot be directly generalized to the LED sources. Used luminaires in which we deal with LED matrixes are seen also in small solid angles. But in this case, a single LED elements are distinguishable by the eye in practically applied distances. Additionally, what is very important, studies showing the impact of such luminaires on the glare impression are not known today.

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