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On the uncertainty of sky scanner data for determination of vertical illuminance

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Abstract

Proper assessment of building facade illumination by natural daylight plays a substantial role in active utilization of renewable solar energy. Theoretical modeling of sky luminance distribution supported by long-term measurements provides indispensable basis for energy efficient building designing. Whole-sky scanners installed on many scientific stations retrieve data for evaluation of daylight climate with more or less accurate manner. Correct quantification of scanner uncertainty is presented in form of the density function analysis in comparison with numerical parsing of the sky coverage after measured data. Synthetic sky luminances are based on the ISO/CIE standard finite in variations and thus computationally inexpensive. Most of currently used sky scanners are not adjusted for vertical illuminance evaluation in terms of error tolerance and more accurate programmable equipment with reduced field of view sensors ought to be designed.

Introduction

Increased demands for energy efficient solutions in building illumination are noticeable mainly in recent decades. Additional lighting in form of natural daylight delivered into the interiors proves to be energy-saving and with its properties and dynamics thereby creating a healthier visual environment for humans. The essential building parts for standard indoor lighting are vertical arbitrarily oriented windows. Intensity of incident daylight for preferred vertical surfaces is therefore crucial in assessing the effectiveness of windows use within the new building constructions. Instruments frequently used for measuring vertical illuminances at the IDMP stations applied worldwide (Ng et al., 2007), (Soler & Gopinathan, 2000), (Rahim et al., 2004), continuously collect data under actual lighting conditions in the exterior locality which enables to to evaluate daylight availability inside any building. A more subtle device for data collection is a whole-sky luminance scanner, that additionally to the overall lighting conditions makes possible to determine sky luminance distribution with more or less precise accuracy. Sky scanners are utilized in various fields of basic and applied research such as lighting technology to specify horizontal and vertical illuminance (Li et al., 2013), photovoltaics for analysis of the irradiance on a tilted surface (Li & Lam , 2004), (Li & Cheung , 2005) as well as in meteorology in form of infrared scanners to monitor a cloud distribution (Feister et al., 2010). Commonly used sky scanners operate with the field of view equals 11o based on the methodology of Tregenza (Tregenza, 1987) while many other systems were developed based on different field of view. A new perspectives for sky scanner utilization force the scientists and firms to develop and construct more precise, low-cost and also portable devices for collecting nearly instantaneous data (Kómar et al., 2013). Frequent disadvantage of these facilities is a restricted field of view and therefore scarce coverage of the hemisphere and thus non reliable data retrieval. The inconsistencies between the evaluated sky scanner data and the real illuminance levels are dealt with the correction factors received empirically for standard sky situations (Ferraro et al., 2011), (Ferraro et al., 2013). Conversion of the acquired data set to illuminance is usually performed by the ISO/CIE recommendation, see e.g. (Kobav et al., 2013), (Markou et al., 2007) using widespread homogenized sky types (Kittler, 1999).

The main objective of this paper is to identify inaccuracies of the sky scanner measurements for determining daylight illuminance on vertical building facades necessary for the lighting research and practice. Theoretical background and numerical experiments are based on a simple analytical model for sky luminance distribution theoretically covering all types of sky situations, it is finite in condition variations and thus computationally inexpensive. Undeniable option is to use homogenized models presented as the ISO/CIE standard (ISO 15469:2004). Normalized density function presented in this paper serves as an indentifier of the zenith angle influence on the vertical illuminance. Simple numerical tool was developed and is called DeF&Err (Density Function & Error) Calculator that also enables to compute sky scanner error depending on the configuration of the input parameters. Free download is available on the website: www.unisky.sav.sk/?lang=en&page=aplikacia. To determine the daylight availability on a building facade is therefore necessary to envisage the optimal field of view and measurement spacing into the supposed design of the sky scanner. This contribution is based on a manuscript "Uncertainty of daylight illuminance on vertical building facades when determined from sky scanner data" submitted to Solar Energy journal.

Illuminance on vertical surfaces for CIE general skies

Diffuse illuminance on arbitrary oriented vertical surface depends on the luminance distribution on the respective part of the sky „seen“ from the surface. The system of homogeneous skies (ISO 15469:2004) describes smoothed luminance patterns that are easily applicable for unassuming modeling. The sky luminance pattern is expressed as the product of relative gradation and indicatrix functions:

$$L_a(z, A) = \left(\frac{\varphi(z)}{\varphi(0^\circ)} \cdot \frac{f(\chi)}{f(Z_s)} \right) L_Z \quad , \tag{1}$$

where *L(z, A)* is the lumiance of a sky element with zenith angle *z* and azimuth *A*, L_Z is the zenith luminance, Z_s is the solar zenith angle, and χ is the angular distance of a sky element from the sun (also called a scattering angle). Zenith luminance is cumputed by two different equations separately for the overcast and clear sky conditions in accordance with the formulae presented in (Kittler, 1999). The gradation function $\varphi(z)$ in the Eq. (1) varies only with the zenith angle of the sky element and it is expressed as follows

$$\varphi(z) = 1 + a \, . \, e^{(b/\cos z)} \quad , \tag{2}$$

while the indicatrix function *f(χ)* is a function of scattering angle χ

$$f(\chi) = 1 + c \, . \, (e^{d\chi} - e^{d\pi/2}) + e \, . \cos^2 \chi \quad , \tag{3}$$

and the calibration coefficients *a, b, c, d* and *e* vary with the sky type. If Z_S is the solar zenith angle and A_S is the azimuth of the sun, then the scattering angle χ can be written in accordance with the cosine rule in the form

$$\cos \chi = \cos Z_s \cos z + \sin Z_s \sin z \cos(A_s - A) \ , \tag{4}$$

where z and A characterize the position of arbitrary sky element. The zenith gradation is $\varphi(0^{\circ})$, while the corresponding value of indicatrix function in zenith is $f(Z_S)$. The Eq. (1) represents a type of the equation with separation of variables, in which two functions are being independent of each other.

Illuminance on the vertical building facade is presented in the Eq. (5) and the azimuthal integration boundaries for the luminance of the sky part seen from the surface element depends on building orientation defined by the azimuth of the normal to the vertical area A_N:

$$D_i = \int_{z=0}^{\pi/2} \sin^2 z \int_{A_N-\pi/2}^{A_N+\pi/2} L_a(z,A)\cos(A_N - A)\,dA\,dz \; . \qquad (5)$$

A density function can determine the behavior of illuminance depending on the zenith angle of the almucantar and its maxima indicate the altitudes with highest overall sky luminance with respect to the vertical plane.

$$\frac{1}{D_i}\frac{d\,D_i}{d\,z} = \frac{\sin^2 z \int_{A_N-\pi/2}^{A_N+\pi/2} L_{a,i}(z,A)\cos(A_N - A)\,dA}{\int_{z=0}^{\pi/2} \sin^2 z \int_{A_N-\pi/2}^{A_N+\pi/2} L_{a,i}(z,A)\cos(A_N - A)\,dA\,dz} \; . \qquad (6)$$

The Eq. (6) shows a density function for the building facade oriented perpendicularly to the azimuth A_N and normalized to the total illuminance on the vertical surface. Subscript i denotes the standardized ISO/CIE sky type and it varies from 1 to 15.

3 Numerical experiments on ISO/CIE skies

Knowing of the scanner uncertainty under various conditions can improve the construction of more sophisticated and precise devices for better evaluation of the effectiveness of daylight usage. The ISO/CIE 15 sky model was chosen for its computational undemanding and simulating a finite number of sky situations under a great variety of conditions. More details are presented in the already mentioned manuscript submitted to Solar Energy journal.

3.1 Calculation tool for density function and sky scanner error

DeF&Err Calculator for luminance sky scanners (for MS Windows) was developed to compute and plot a normalized density function in accordance with the Eq. (6) and the sky scanner error in vertical illuminance evaluation. The program comes with a simple graphical user interface (GUI) to choose the CIE sky type, solar position, orientation of the vertical plane and the angular diameter of the sky patch measured by the scanner. DeF&Err Calculator creates the outputs for density function in ASCII text file as well as a simple preview. Graphical output is generated from a data file using „plot2d“ software distributed under free BSD-style license which creates a plain compressed bitmap image. The output text file for the sky scanner error is in standard ASCII encoding and can be processed in the future. „Show Results“ button opens the text and the graphic files in user`s default programs. Fig. 1 presents the interface of the tool with generated output files.

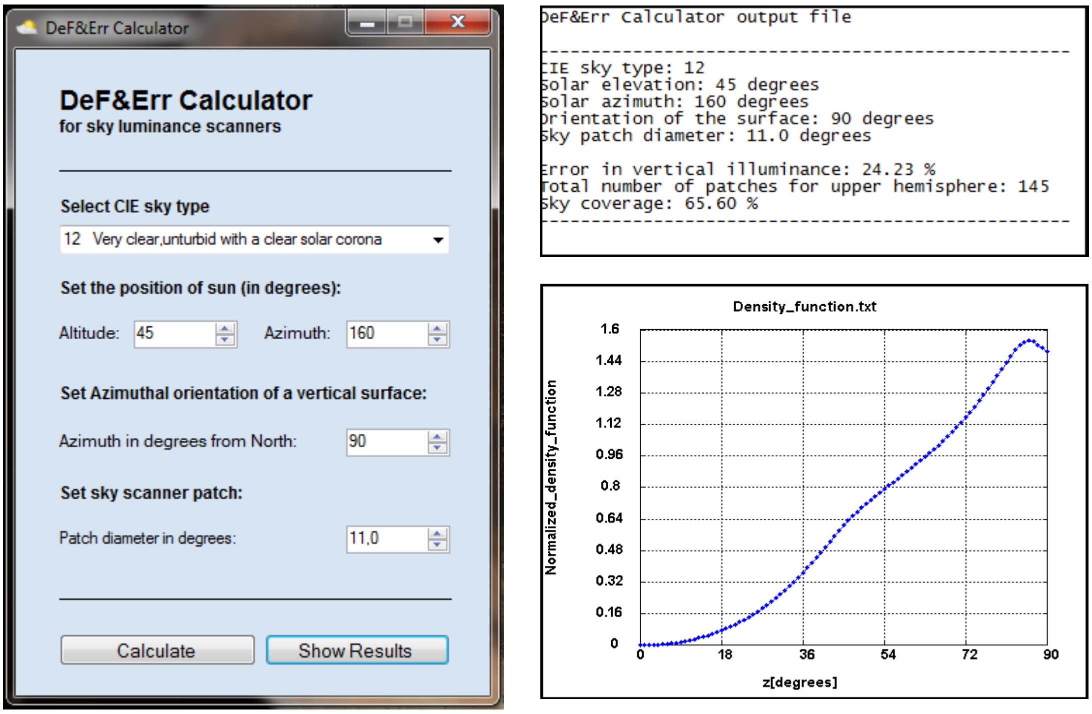


Figure 1 DeF&Err Calculator for sky luminance scanners with GUI and output files.

3.2 Normalized density function for selected ISO/CIE skies

To achieve higher accuracy of vertical illuminance when sky scanner data are evaluated compared to simultaneous measurements with luxmeters it is important to identify those parts of the sky that contribute to the illuminance level the most. Although commercial scanners are constructed mostly without change to various purposes alternative design of the programmable scanner with denser sky coverage of almucantars can be proposed. This is particularly essential for vertical illuminance evaluation wherever the considerable uncertainty occurs even at relatively small field of view, i.e. acceptance angle of luminance sensors.

Normalized density function given by the Eq. (6) allows to analyze a tendency of vertical illuminance coming from different sky parts under various conditions. Fig. 2 depicts density functions plotted for selected overcast ISO/CIE sky types and different solar zenith angles. The vertical surface is faced towards East. In cases of azimuthally uniform skies 1 and 3 and even if not plotted for sky type 5, the density function dependency on the solar altitude is not indicated. For sky luminance gradation 1:3, i.e. sky type 1) lacks additional data coverage on the almucantar with zenith angle around 55^{o}. The largest contribution of incoming light from low elevation angles is in case of sky type 3 and the projected range of scanned patches increases towards the horizon equally as it is valid for EKO type sky scanners. If the position of the sun is indicated behind the cloud layer the maximum of the density function is slightly shifted towards the solar almucantar (see sky types 2 and 4).

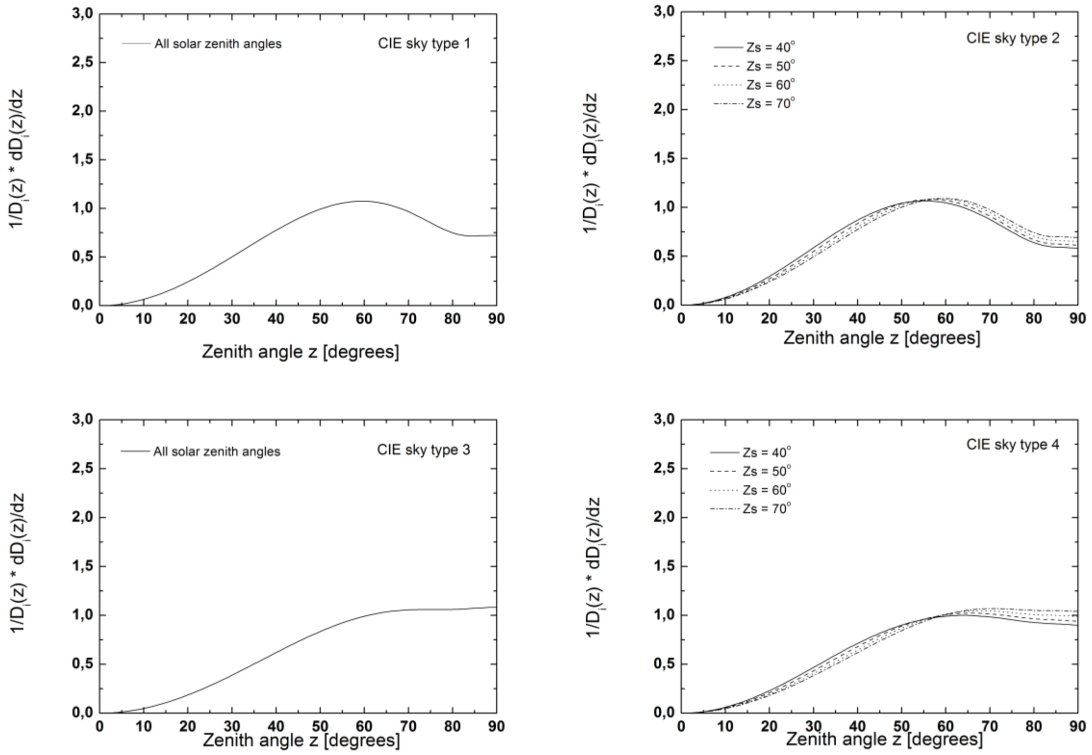
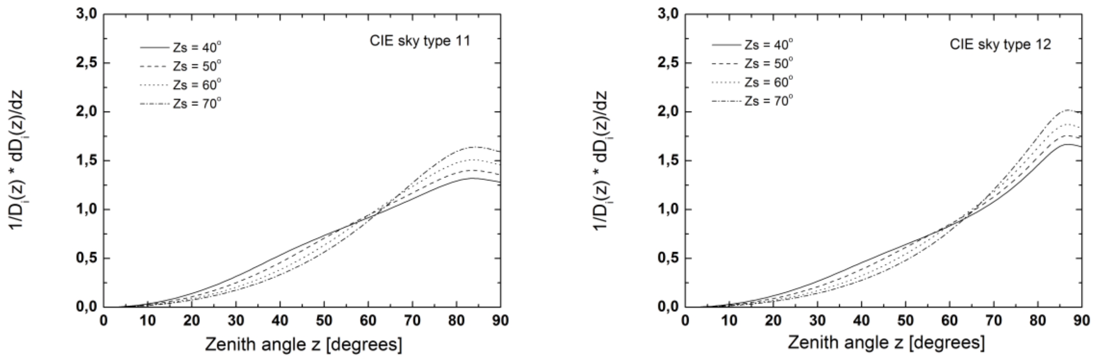


Figure. 2 Normalized density function for selected overcast ISO/CIE skies and various solar zenith angles. Vertical surface is oriented toward East.

Fig. 3 presents the density functions for cloudless situations for different solar zenith angles similarly as in previous case. Dominant influence on the vertical illuminance is caused by the area close to the horizon, the local maxima of density functions additionally occur close to the solar almucantar in cases of higher altitudes of the sun. Therefore, scanning with densely more spaced patches of those sky parts could enhance the accuracy of evaluated vertical illuminance.



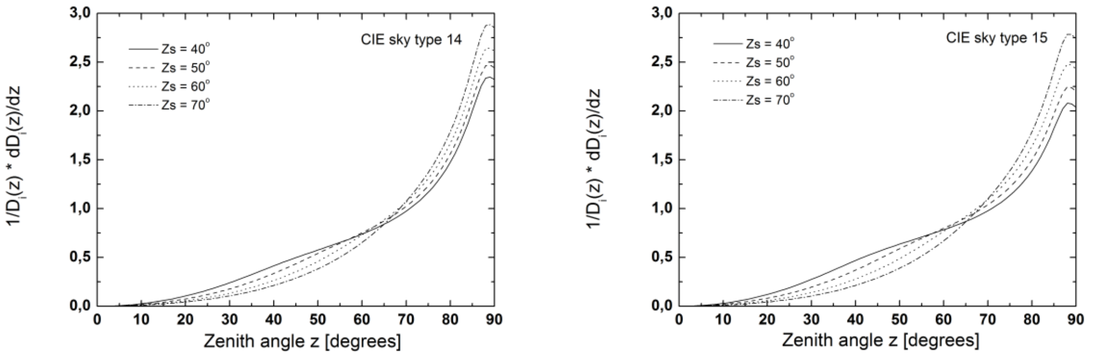


Figure. 3 Normalized density function for selected clear ISO/CIE sky types and various solar zenith angles. Vertical surface is oriented toward East.

Figs. 2 and 3 are the only special case examples how to make sky scanning more efficient and accurate for whole-sky measurements. DeF&Err Calculator permits the user to calculate density functions for arbitrarily oriented planes, solar position and sky type.

3.3 Sky scanner accuracy for various field of view

Sky scanners manufatured by private companies are mostly designed with different fields of view and also their assembly provides scanning steps with sky positions distributed not quite evenly. Scientists with different fields of interest typically ougtht to retrieve data from various sky parts with different density of measurement pathes and thus they prefer sky scanners with diverse parameters. It should be keep in mind that the higher scanner resolution the more is extended scanning time and thereby are losing the advantage of almost instantaneous measurements. In rapidly changing conditions such as under discontinuous cloud fields such delays will cause an certain devaluation of the informations. Therefore, it is necessary to decide on a compromise between a scanning time and the amount of data collected by the device.

Fig. 5 shows the mean error in vertical illuminance for 15 ISO/CIE skies for three different field of view (FOV) and facade orientation towards West and North. Azimuth of the sun is 180 degrees and errors are averaged over the solar zenith angles within 1 - 89^{o}, whichever the smaller the altitute of the sun the higher is the recorded error.

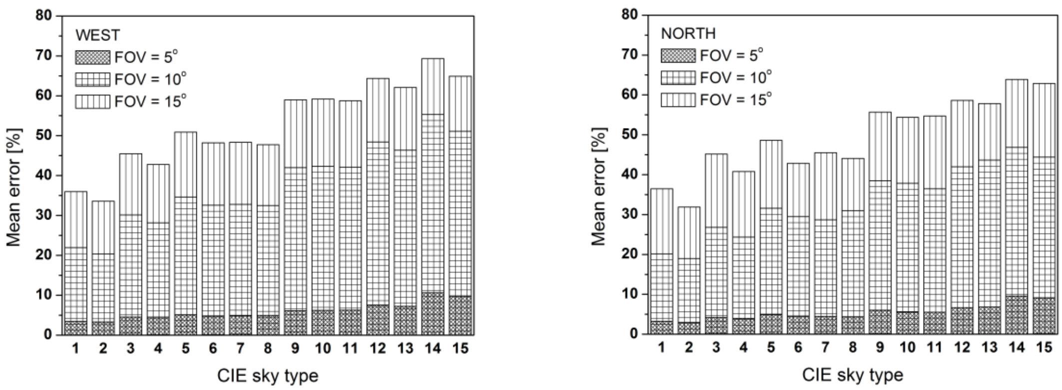


Figure. 5 Mean error of vertical illuminance evaluated from sky scanner data if different sky patches of circular diameter are measured by scanners with three FOV acceptance angles.

It is evident, that evaluating vertical illuminances from data measured by sky scanners with field of view higher than 10^o causes errors that over 20% for the overcast skies and these reache 50% for cloudless sky conditions. Scanners with a wider field of view are therefore far beyond the reliability of the measurements when taking into account the density function analysis mentioned above. After Fig. 5 more accurate scanners with a field of view about 5 degrees can be designed to achieve quite preise results.

4 Conclusions

A straightforward proposal is introduced to improve the precision of luminance sky scanners for evaluation of daylight availability on vertical building facades. As a proof was used a computationally simple finite model of 15 ISO/CIE sky types opted to present the tendencies of the individual almucantars to contribute to the uncertainty of vertical illuminance. For this purpose, a simple tool DeF&Err Calculator was developed to compute normalized density functions clearly representing the importance of zenith angles covering more or less densely in measured by data. Scanner inaccuracy derived from its field of view and sky patches spaced uniformly show a consequential errors already in currently used devices. Nowadays, a demand for more accurate and sophisticated equipment is required due to the creation and verification of more precise sky luminance / radiance distribution models and therefore examining the efficient utilization of daylight for energy efficient building designs as well as the availability of scattered solar radiation for photovoltaic applications. The current scanning techniques are often ineffective and data analysis leads to uncertainty, that are beyond the border of tolerability. Solving this deficiency could be a programmable sky scanner with the selection of a stepping density in several sky parts with reduced FOV up to 5 degrees in order to take into account outdoor lighting conditions and the measurement purpose..

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