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Development of synthetic hemispheric projections suitable for assessing the sky view factor on horizontal planes

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ABSTRACT

The solar radiation balance in buildings has a significant impact on their energy needs, as well as on their potential for buildings-integrated photovoltaics (BIPV) energy production. It also influences the potentials of daylight, its healthiness and sustainability. Solar radiation models for urban environments require the characterization of the obstruction degree to which each point is subjected due to other buildings, topography, vegetation, etc. This characterization is carried out with the parameter known as sky view factor (SVF). In this paper, we check that significant disagreements exist in the literature with respect to the definition of SVF. Most published methods show that SVF admits a geometric interpretation as a ratio of projected sky surface versus the global surface of the sky vault projected on the same system. Nevertheless, the type of projection depends only on the authors' considerations. The geometric comparison of the methods opens a new way to explain their differences. This paper presents a general mathematical method to obtain projection equations, which allows the interpretation of SVF as a surface ratio. It is also proposed the adequate projection for horizontal surfaces under the hypothesis of angular distribution of diffuse radiance based on Moon–Spencer's model.

1. Introduction

Incident solar radiation in buildings determines the energetic balance and healthiness of rooms. It also supports heating systems in cold seasons and acts as a natural light source. Excess insolation, however, may have a negative impact due to two main reasons, namely: (i) solar radiation can be a heating load that needs to be balanced with air conditioning; and (ii) it may cause glaring and, as a consequence, natural lighting can be uncomfortable. The development of distributed energy networks, together with energy generation in situ through building-integrated photovoltaic (BIPV) systems, make solar radiation on roofs and facades to be a potential resource of the building.

The high number of obstructions in urban environments, however, remarkably determines solar incidence on facades and horizontal surfaces [1,2]. As a result, it affects differently the direct, diffuse, and reflected components of solar irradiance (Eq. (1)). On the one hand, direct shading studies based on the astronomical movement allow the characterization of the obstructions effect on the direct component. On the other hand, to obtain the characterization of the diffuse component, we define SVF as the diffuse irradiance percentage impinging on an obstructed, inclined plane versus a horizontal plane with no obstructions (Eq. (2)).

$$I = I_{DN}\cos \quad i + I_{dH} f(SVF) + I_{GH}\rho\, GVF, \tag{1}$$

$$\text{when} \quad \left|i\right| > 90, \cos i = 0,$$

$$SVF = \frac{I_{d\beta}}{I_{dH}}. \tag{2}$$

Numerous studies have focused their interest on the determination of SVF in vertical wall surfaces. Compagnon [3], Kapchun et al. [4], Papadakis et al. [5] focus their attention on SVF characterization, as it determines the photovoltaic potential in BIPV installations, or some characteristics related to the equivalent psychological temperature inside buildings.

The definition given by Eq. (1) entails that SVF depends on the angular distribution of the diffuse radiance in the sky vault. It is known that for obtaining accurate predictions of solar irradiance in any unobstructed plane it is necessary to use suitable models that take into account the correct angular distribution [6]. The predictive capacity of the isotropic model, radiance uniform distribution of radiance for every direction in the sky vault, is surpassed by

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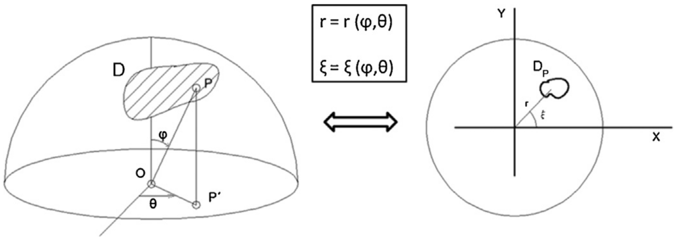

Fig. 1. Proposed transformation.

anisotropic models [6,7]. They consider the radiance $R(\varphi,\theta)$ coming from a spatial direction OP depending on azimuth angle (θ) and zenith angle (φ) represented on Fig. 1. Similarly the angular distribution of the luminance from the sky vault exhibits frequently a marked anisotropy [8]. Nusselt [9], Oke [10], Johnson and Watson [11], Steyn [12] and Hay et al. [13], and Holmer et al. [14] used the isotropic model to estimate SVF. In fact, the classification and systematization of methods carried out by Chen et al. [15] and Kapchun et al. [4] reflect that the isotropic method is the most widely used. Ivanova [16], nevertheless, considers the angular distribution of the background radiance by Muneer [17] as the most adequate method. Otherwise, Rakovec and Zaksek [18], and Tian et al. [19] define SVF as the solid angle fraction with which the obstructed sky vault is seen versus a non-obstructed sky vault (2π sr). Finally, some authors estimate the value of SVF as the percentage of surfaces on images obtained by all-sky cameras.

Maor and Appelbaum [20] and Kapchun et al. [4] use anisotropic models to calculate irradiances on inclined planes by using SVF values based on the isotropic model.

Hemispheric projections allow the representation of points on a spherical surface (i.e., the sky vault on a plane chart). Hemispheric representations of the sky vault allow the correct understanding and decision-making processes in problems related to shading or solar access. Teller et al. [21], Ramírez-Faz and López-Luque [22], Whan et al. [23] and Littlefair [24] recommend the choice of the most adequate hemispheric projection according to the metrical properties and the variables of each study. In our study, we consider the following projections:

- Stereographic projection. This type of projection preserves angular distances. The plane representation of 3D circumferences included in the 3D sphere is transformed into 2D circumferences. Pleigel [25] developed the globoscope, an optical instrument for obtaining stereographic images directly from the reflection of the sky vault in a parabolic mirror. This projection is widely used in both architecture and the field of graphic description of obstruction profiles. Ivanova [16], Teller et al. [21], and Suoza et al. [26] use it only as a means of representing graphically the existent obstructions. An et al. [27] use a definition where they assign metric properties to SVF, as they consider SVF as the ratio of non-obstructed sky area in the stereographic projection versus the projected area in the semi-vault.
- Orthogonal projection. Nusselt's analogy [9] shows that the sky view factor based on the isotropic model coincides with the 2D surface ratio of the obstructed sky of the orthogonal projection. Torres et al. [28] show the usefulness of this method to determine shape factors. Souza et al. [26], despite being focused on the graphic study to obtain SVF, only show the lateral orthogonal projection. Considering this property, Márquez García et al. [29] propose an estimation mode for SVF. They consider a set of rays emerging from the inclined surface and, as a consequence, the authors demonstrate that SVF is correctly estimated as the ratio of rays that are non-incident neither on the floor nor on the obstructions. Conceptually, the directions used coincide with those described by Ratti and Richens [30].
- Lambert projection or equal-area hemispherical. In this projection, the solid angles are proportional to the projected surfaces. This property permits the SVF to be determined, according to Rakovec and Zaksek [18] and Tian et al. [19], as the ratio of non-obstructed sky area in the projection versus the projected area of the semi-vault.
- Polar projection. The distance from every 2D point representation to the center of the image is proportional to the zenith angle of the 3D original point. Ideally, fisheye lenses produce polar projections. Theoretically, this is the projection considered to introduce metric parameters in hemispheric all-sky camera's photographs, as well as to develop methods such as Johnson and Watson [11], Steyn and Hay [5], Holmer et al. [14], and Chapman et al. [31]. Matzarakis and Matuschek [32] follow Rayman's model, where SVF is estimated as the area percentage on the polar chart.
- Cylindrical projection. This projection appears in the form of rectangular chart. The horizontal axis shows the azimuth of sky elements, while the vertical axis represents the altitude angle. Despite the lack of metric features, Gharakhani and Pillay [33] use the cylindrical projection as a SVF reference chart. Redweik et al. [34] suggest a modification in Ratti and Richens' method for horizontal surfaces [30]. These authors propose a calculation method for SVF that gives equal weight to each surface portion of the cylindrical chart.

The study of SVF for radiative calculations shows a formal analogy with the calculations of sky component (SC) in the study of natural lightning. In this field, Waldraw developed graphic projections adequate for SC calculations. The utility of the generation of adequate projections for each illuminance was stated by Ramírez et al. [35], who developed specific projections to obtain the SC parameter in windows and vertical wall surfaces.

This paper proposes a new type of projection that permits the representation of the visible sky semi-vault from a horizontal surface. This projection presents metric features directly related to Eq. (3), concerning the radiance angular distribution of Moon–Spencer's anisotropic model [36]. From a practical point of view, this projection is a step forward in the way started by Ivanova [16], due to the fact that it allows the determination of the obstructive potential in the horizontal plane of complex surfaces under anisotropic sky radiance model. We call Moon–Spencer projection (MS_b) to the one presented in this paper.

$$R(\varphi,\theta) = R_Z \frac{1 + b\cos\varphi}{1 + b}, \tag{3}$$

where:
$R(\varphi,\theta)$ = radiance in point P,
R_Z = radiance in the zenith of the vault, b = parameter depending on sky conditions,
φ = zenith angle,
θ = azimuth angle.

Firstly, and as a previous stage, it is developed and show the general mathematical method to obtain the equations of hemispherical projections derived from any angular distribution of radiance.

2. Methodology

2.1. Ramírez's mathematical method to develop hemispheric projections

This method allows the graphical study of all physical magnitudes (C) satisfying Eq. (4). For that, the method assigns a plane surface to these physical magnitudes. That is, C is obtained by the integral in the directions of zenith angle φ and azimuth θ. The