Towards a Generalized, Fully-anisotropic Transposition Model

PVPMC Webinar on Solar Resource Assessment
June 24, 2020

Martín Herrerías Azcué
HLRS - NUM, Stuttgart
herrerias@hlrs.de
Motivation

Empirical transposition models are limited:

• Fitted on shade-free conditions
• No room for arbitrary distributions (clouds!)
• Diffuse shading is difficult to localize
• Rigid in their inputs
  – GTI sensors?
  – Shaded sensors?

Applications:
  – Nowcasting (O&M)
  – Short-term forecasting
  – Site assessment
  – Bi-Facial modeling?
  – ...

Source: Capdevila, Herrerías & Marola (2014)
Prior art

- **View factors**
  - Evans & Coombe (1959) / Anderson (1964)

- **Continuous Distribution Models (CDM's) for Sky Luminance**
  - Hooper & Brunger (1980)
  - Nakamura (1985)
  - Perez et al. (1993)
  - Kittler & Darula (2002)

- **Masks on CDM's**
  - [Forest Ecology / Building Simulation]
  - Bosch et al. (2010)
  - Ivanova (2013)

- **Discretized CDM's**
  - Satel-Light Project (1996)
  - Goss et al. (2014)
Irradiance Transposition

The global effective irradiance incident on a point on a PV surface is the integral (over the complete unit sphere) of the incoming spectral radiance $L_{e,v}(\theta, \phi, \nu)$ [W/(m$^2$·sr·Hz)], from each particular direction $p(\theta, \phi)$ weighted by the spectral response of the PV material $S_R(\nu)$, and by a function $g(\gamma)$ of the incidence angle between the surface normal $u$ and the light source $p$:

$$I_u = \int_0^{2\pi} \int_{-\pi/2}^{\pi/2} \int_{-\infty}^{\infty} L_{e,v}(\theta, \phi, \nu) S_R(\nu) g(\gamma) \cos \theta d\nu d\theta d\phi$$

$$g(\gamma) = |\cos \gamma| f_{IAM}(\gamma), \quad \gamma = \cos^{-1}(p^T u)$$
Transposition by View Factors

If we assume that all light comes from an underlying far field radiance distribution, and that we can divide the unit sphere into a set of patches \(\{s_1, s_2, \ldots, s_n\}\) with approximately uniform effective radiance \(\{\tilde{L}_1, \tilde{L}_2, \ldots, \tilde{L}_n\}\), we can write:

\[
I_u \approx \sum_{j=1}^{n} \int_{-\infty}^{\infty} L_{e,v}(j,\nu) \, S_R(\nu) \int_{s_j} f_{u,j}(\phi, \theta) \, g(\gamma) \, dA
\]

\[
I_u \approx \sum_{j=1}^{n} \tilde{L}_j F_j = F_u^T L_t
\]

Where \(f_{u,j}\) is the fraction of \(\tilde{L}_j\) that is visible from \(u\).

We call \(F_u = \{F_1, F_2, \ldots, F_n\}_u\) the view factors for regions 1 to \(n\) at point \(u\), and \(L_t = \{\tilde{L}_1, \tilde{L}_2, \ldots, \tilde{L}_n\}_t\) the \(n\) irradiance components at time \(t\).
View Factors by Custom Projection

Typically we set $f_{u,j} = 1$ for all points $A_u$ of the far-field directly visible from $u$, and zero otherwise (no reflections*). Then the view-factors become a function of geometry only:

$$F_j = \iint_{s_j \cap A_u} g(\gamma) \, dA$$

And it is easy to find a projection function $r_p(\gamma)$ that turns this integral into an area over a plane:

$$A_{j,p} = \iint_{s_j \cap A_u} dA_p = \iint_{s_j \cap A_u} g(\gamma) \, dA$$
$$dA_p = r_p(\gamma) \, dr_p d\phi = |\cos \gamma| f_{I AM}(\gamma) \sin \gamma d\gamma d\phi$$
$$r_p^2(\gamma) = \int_0^\gamma f_{I AM}(\gamma) \sin 2 \gamma d\gamma , \ 0 \leq \gamma \leq \pi/2$$
CDM's as Transposition Model

Empirical Continuous Radiance Distribution Models can be used as a drop-in replacement for transposition models:

• Igawa, Koga, Matsuza & Nakamura (2004)
  – Parametrization of std. (gradation x scattering) function in terms of a single „Sky-index”
  – Fitted to radiance [W/m²sr], not luminance [cd/m²sr]

• Discretizing the model seems like extra-steps, but can reduce computational effort and memory requirements:
  
  Quadrature points : $O(u \times q^2)$
  
  View – Factors : $O(u \times n^2 + q)$
CDM's as Transposition Model

• NREL's Data for Validating Models - Marion et al. (2014)
  
  – Eugene, Oregon (44°N, 123°W, 145 mASL, 44° tilt)
CDM's as Transposition Model

- NREL's Data for Validating Models - Marion et al. (2014)
  - Golden, Colorado (39.7°N, 105.2°W, 1798 mASL, 40° tilt)
CDM's as Transposition Model

- NREL's Data for Validating Models - Marion et al. (2014)
  - Cocoa, Florida (28.4°N, 80.5°W, 12 mASL, 28.5° tilt)
Effect of discretization?

• Integration errors increase with patch size and steeper gradients

• Sign of bias ~ gradation

• Final transposition error (no shading!) rather insensitive to anything above ~10 sky regions.

• Moving circumsolar regions don't seem to reduce error, except in simplest cases
Effect of discretization (cont.)

![Graph showing the effect of discretization on RMS values.](image-url)
Estimating Radiance using View Factors

Given a set of sensors \(\{1 \ldots m\}\) (pyranometers, reference & calibrated cells, faceted-sensors, etc.), we can calculate their view-factor matrix \(F_M = [F_1, \ldots, F_m]^T\) based only on their geometrical configuration (position, orientation, shade-masks, etc.), and use it as a set of constraints for the unknown \(\hat{I}_t\) based on measurements \(I_{M,t} = [I_{m,1} \ldots I_{m,n_m}]^T\):

\[
F_M \cdot \hat{I}_t = I_{M,t}
\]

Sadly, in most cases, we'll have less sensors than regions, and the problem will be underdetermined (\(F_M^T F_M\) will not be invertible).
Least-Norm Solution

One possibility is to start with a “reasonable assumption” $L_o$ (derived from empirical models) and use sparse-regression to find a solution for the problem:

$$F_M \cdot (L_o + \varepsilon) = I_{M,t}$$
$$F_M \cdot \varepsilon = I_{M,t} - F_M L_o$$

that minimizes a given norm $|\varepsilon|_p$ of the vector of differences $\varepsilon$ with the empirical model.
Test case: Least $L_2$ norm (Ridge Regression)

Data from the Karl von Ossietzky University of Oldenburg

- Secondary Standard Pyranometers for:
  - GHI, DHI
  - South 45°
  - South 60°
  - South-East 45°
  - South-West 45°

- 10000 points at random, from 1 year of 1-minute data
Least-Norm Solution: GHI + S 45° (Uni. Oldenburg)
Least-Norm Solution: GHI + S 60° + SE 45° (Uni. Oldenburg)
Future Work

- Decomposition Problem: hard & soft constraints, uncertainty and smoothness priors to reduce overfitting
- Estimating diffuse fraction
- Testing & Validation, new data sets and sensor configurations
- Spectral content correction for individual components
- Obstacle & terrain (self) shadows, non-Lambertian albedo
- Performance Optimization
Thanks

• Annette Hammer, Jorge Lezaca, Hugo Capdevila,…

• University of Oldenburg, NREL, GroundWork and PVPMC

• Everyone, for your attention!
References

References (cont.)


• Ineichen, P., 1996. Use of Meteosat data to produce sky luminance maps. Satellight, Commision of the European Communities, Bergen.


