2.2.5: Specification of reduced-order dynamic models and associated weather processing tools in order to provide a library of component models for control system simulation.

Jeffrey R. S. Brownson & Lucas Witmer

January 31, 2012

Summary

Work was pursued to investigate developing sky radiative models for the Modelica systems programming language and compare those results to sky radiative models used in current simulation tools such as TRNSYS and Matlab. TRNSYS and Matlab softwares are commercially available, and have been used extensively to implement sky radiative algorithms linked with component-based building simulations and control implementations. While the softwares do require financial investments to access the simulation tools, the highly modular components are adaptable to new modeling improvements that emerge in the literature.

Researchers found that traditional isotropic and anisotropic sky radiative algorithms had been programmed by Dr. Michael Wetter of LBNL for the Modelica simulation language as a part of the *Building Controls Virtual Test Bed* (BCVTB). The team was unaware of this existing development at the time of initiating the research, and the functionality appears appropriate for most building simulations requiring a component-based sky radiation model. However, the components for the BCVTB were found to require a commercial license to the Dymola front-end software to be useful for new programming developments. As the license for full academic use was cost-prohibitive given the funds available to the research team, open-source software was explored for the front-end. Currently available open-source software was found to be unreliable when tested across Microsoft, Linux, and Macintosh operating systems. Only simple Modelica components were

able to be explored, and the BCVTB suite of components was largely unaccessible. From the research, we therefore recommend caution in proposing Modelica as a “free” alternative to commercially available simulation software such as TRNSYS or Matlab.

Review of Irradiance Component Estimation on Horizontal Surfaces

Irradiance is used in this setting to specifically refer to the radiative flux (W/m^2) of solar shortwave energy (∼250-2500 nm) incident upon terrestrial surfaces. When that radiative flux is integrated over time into a fluence (J/m^2), the term irradiation is used. Current irradiance/irradiation models present the fractional contributions of the total solar energy (also termed *global*) as geometric components from the sun (beam, circumsolar), the diffuse sky, and for tilted surfaces (non-horizontal surfaces) reflective terrestrial surfaces (ground reflectance, or albedo, and horizon diffuse) have been assessed.

There have been 50+ years of development of empirical correlations among *global* (or *total*) downwelling shortwave irradiation (J/m^2) and *diffuse* and *direct* (or *beam*) contributions upon a horizontal surface.[5] Since Liu & Jordan’s work in the early 1960s, many empirical sky models have been proposed to separate or “decompose” irradiation components. The models all use measured hourly radiation data to validate the empirical fit. Measurements tend to be collected and extrapolated from a singular weather station pyranometer (measuring shortwave (250-2500 nm) downwelling irradiation), or by using accumulated or simulated data for Typical Meteorological Year synthetic weather data sets. In assessing the 50+ years of direct/diffuse separation research, Gueymard found that the empirical correlations that contribute to dividing a global horizontal irradiation measure tend to break down significantly for time steps less than one hour, and are particularly poor at estimating direct normal irradiation (DNI).[6] Gueymard confirmed that experimental errors and local climatic factors are embedded in such models. A detailed analysis for 36 models were evaluated at 4 sites, yielding inconsistent results and some high bias. They assessed models that require more inputs than just the daily clearness index for total/global irradiation (K_t) (Reindl, Perez, Skartveit), or newest models, were found not to perform better, globally. In all there, was large scatter in hourly results, and even larger scatter in 1-min results to essentially indicate no correlation at all.[6] This breakdown may be critical to renewable energy technologies with brief characteristic time steps, such as photovoltaics, but tend to be of less consequence to technologies with longer time steps (higher thermal capacitance) such as building zones and façades.

Review of Component Models on Titled Surfaces

When only the *global* horizontal irradiation is known (typical of a shortwave pyranometer measurement), researchers rely on empirical correlations between geometric configuration, cloudiness, and atmospheric clarity to determine the *components* of the model.[3] Data suggests that the diffuse components consist of three general contributions: *isotropic, circumsolar diffuse*, and *horizon brightening* as depicted in Figure 1.[3] The beam component of the model is closely associated with the circumsolar diffuse component. Many sky radiative models have been developed and employed for various purposes, but can have inaccuracies as high as 20% as well as biases ranging from a few percent to significant levels of 10%-20%.[4]

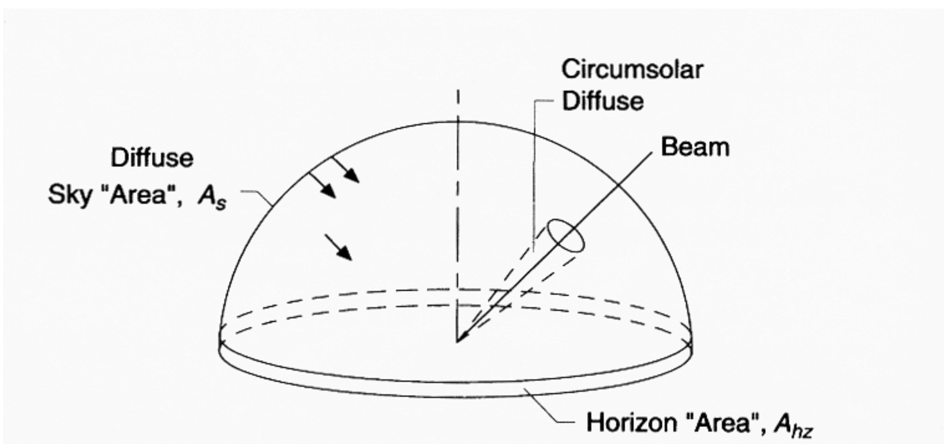

Figure 1: Sky Dome Radiative Schematic adapted from Perez et al. 1988 and [3]

The general equation for the total irradiation (J/m^2) on a tilted surface in terms of the direct, diffuse, and reflected components is described in Equation 1.[3] Here, the five terms of the equation respectively represent the beam contribution, the isotropic diffuse contribution from the sky, the circumsolar diffuse, the diffuse from the horizon region, and the reflected radiation streams from buildings, fields, and other surrounding objects. A_c is the area of the collector, I is an amount of irradiation further defined by subscripts, F is a radiation view factor from one body to another, T is total, b is beam, d is diffuse, and ρ is the diffuse reflectance of any surface.

$$\begin{aligned} A_c I_T = & I_b R_b A_c + I_{d,iso} A_s F_{s-c} + I_{d,cs} R_b A_c \\ & + I_{d,hz} A_{hz} F_{hz-c} + \sum_i I_i \rho_i A_i F_{i-c} \end{aligned} \tag{1}$$

The most widely used application of this model is the Perez Diffuse Irradiance Model for Tilted Surfaces.[7] Other models are available in solar simulation softwares such as TRNSYS that involve computationally faster algorithms for large models, and which provide similar results to the Perez model for components of irradiation.

Review of Simulation Tools

Many tools have been employed to integrate irradiance models with various system simulations. Each tool has its advantages, but there is currently no single, perfect tool for all modeling scenarios. As such, an evaluation of several tools has been undertaken to evaluate the weather processing potential of each transient and dynamic modeling tool for control system simulation.

Solar Energy Conversion System Simulation

Solar energy conversion systems have had several tools developed for predicting performance. A full report of available tools has been developed at Sandia National Laboratory by Geoffrey Klise and Joshua Stein and is available online. A widely used and versatile tool, MATLAB is often employed for control system modeling. MATLAB/Simulink sports a PVtoolbox program for integration of weather simulation and irradiance processing within MATLAB.[9]

Building Energy Performance Simulation Software

There are many building energy performance simulation programs that are readily available. Some are more detailed and versatile than others, while some of the simpler ones allow for rapid modeling without a significant user learning curve. A full report of simulation tools available in 2005 can be found by Crawley et. al.[8] These software tools continue to be developed and some of the tools reported in the Crawley et. al. report have changed over the last six years. Regardless, it still portrays a good picture of the diversity in program options available to a building energy engineer.

One of the most versatile simulation tools is the Transient System Simulation (TRNSYS) software. Many of the tools, including TRNSYS, include a full suite of Typical Meterological Year (TMY) weather files. Components within the TRNSYS Simulation Studio allow for the dynamic processing of radiation inputs from either these included weather files or any input stream of weather data, including data on much finer time scales such as one minute time step data from the Surface Radiation (SURFRAD) network or any local weather station with an available data stream.

Modelica

Modelica remains in an early stage of development. Current goals of the developers include the development of the simulation environment and the further design and development of the language itself. Debugging support is still in the development stage as well. The open source OpenModelica Connection Editor (OMEdit) is a very basic editor for basic simulations, but is inadequate for wide spread implementation. As such, various professional modelica front-ends have been employed by researchers to continue the development work of this modeling tool. Modelica was found to be extremely limited without a professional site license of the Dynamic Modeling Laboratory (Dymola), one of the most widely used professional editors for Modelica.

In the research undertaken for this work, sky models, or component implementations, were found in the Modelica Buildings package developed by Michael Wetter, et al., at the Lawrence Berkeley National Laboratory. Three components are currently available: diffuse isotropic irradiation on a tilted surface, Perez anisotropic irradiation model for a tilted surface, and the beam (or direct) geometric relation for irradiation on a tilted surface.

List of Irradiation in the Modelica Buildings Package, within the *BoundaryConditions* class.

The following list incorporates the currently available models for components of solar irradiation in the Modelica Buildings package.

..SolarIrradiation.DiffuseIsotropic: Diffuse solar irradiation on a tilted surface with an isotropic sky model

..SolarIrradiation.DiffusePerez: Hemispherical diffuse irradiation on a tilted surface using Perez's anisotropic sky model

..SolarIrradiation.DirectTiltedSurface: Direct solar irradiation on a tilted surface

References

[1] Wetter, Michael (2011) *Building Controls Virtual Test Bed.* https://simulationresearch.lbl.gov/bcvtb. Accessed Dec. 16, 2011.

[2] Wetter, Michael (2011) *Modelica Library for Building Energy and Control Systems.* http://simulationresearch.lbl.gov/modelica. Accessed Dec. 16, 2011.

[3] Duffie, J. A. and W. A. Beckman (2006) *Solar Engineering of Thermal Processes, 3rd ed.*, John Wiley and Sons, Inc.

[4] Myers, Daryl (2003) *Solar Radiation Modeling and Measurements for Renewable Energy Applications: Data and Model Quality* www.nrel.gov/docs/fy03osti/33620.pdf. Accessed Dec. 16, 2011.

[5] Bird, Richard E. and Hulstrom, Roland L. (1981) *A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces.* http://rredc.nrel.gov/solar/pubs/PDFs/TR-642-761.pdf. Accessed Dec. 16, 2011.

[6] Gueymard, Christian A. (2010) *Progress in Direct Irradiance Modeling and Validation* http://www.ases.org/papers/186.pdf ASES Paper. Accessed Dec. 16, 2011.

[7] Perez, R. Seals, R., Ineichen, P., Stewart, R. Menicucci, D. (1987) *A new simplified version of the perez diffuse irradiance model for tilted surfaces.* Solar Energy, 32(3). 221-231.

[8] Crawley, Drury B., Hand, J. W., Kummert, M., Griffith, B. T. (2005) *Contrasting the capabilities of building energy performance simulation programs.*
http://apps1.eere.energy.gov/buildings/tools directory/

[9] Klise, Geoffrey T. and Joshua S. Stein (2009) *Models Used to Assess the Performance of Photovoltaic Systems.*

http://www.physics.arizona.edu/ cronin/Solar/References/PV System Modeling/SAND2009 208258.pdf