SOFTWARE FOR WINDOW SOLAR GAIN ANALYSIS

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ABSTRACT

Three computer programs have been developed for use in assessing solar heat gain through windows in buildings. SUNSPEC calculates the direct beam and diffuse sky solar spectral and broadband irradiances incident on an arbitrarily oriented plane, for any position of the sun in the sky relative to the receiving plane. The calculations are for a cloudless sky and allow the user to specify the concentrations of various atmospheric gases and particulates. AWNSHADE calculates the unshaded fraction of a vertical window's area when illuminated by direct bearn solar radiation. It also calculates an approximate effective unshade fraction for a window illuminated by isotropic radiation from the sky and from the ground. Shading geometries allowed by AWNSHADE include awnings with horizontal or inclined sidewalls, overhangs, and vertical sidefins with horizontal or inclined top edges, and combinations of these. SUNPATH calculates the position of the sun in the sky for any day of the year, time of day, and location on earth, as well as sequences of positions, called sunpaths, on one or more selected days in the year. It also plots sunpath diagrams on the screen and to print files.

INTRODUCTION

Tools are needed that can be used early in the building design process for window aperture placement and sizing in relation to solar movement and in making decisions regarding additional shading devices such as awnings, overhangs, and sidefins. A suite of three PC-compatible computer programs is now available for this use. SUNPATH[1], SUNSPEC[2], and AWNSHADE[3], are available from the Florida Solar Energy Center (FSEC).

The first calculates the position of the sun in the sky for any latitude, longitude, time of day, and day of the year, or a range of such positions, depending upon the user's interests. It can also be used to calculate the dates and times that the sun will be within a specified range of directions in the sky, and the times of sunrise and sunset for any location and date. The program, and the linked program PATHPLOT that comes with it, can be used to plot a sunpath chart for any location, providing in one diagram the coordinate paths of the sun through the sky for each of a number of days spaced equally over the course of a year. Charts such as these are useful in determining the locations of exterior shading devices and window placement in relation to building needs for heat gain or avoidance.

The second program, SUNSPEC, calculates the cloudless sky spectral irradiance distribution of direct beam solar radiation, as well as diffuse sky and ground-reflected spectral irradiance, incident upon any arbitrarily oriented plane, for a variety of user-selected atmospheric conditions and for any position of the sun in the sky. SUNSPEC is a user-friendly implementation of Gueymard's SMARTS solar spectral irradiance algorithm[4]. SUNSPEC also integrates these spectra to determine the total irradiances and illuminances from sun, sky, and ground incident upon a given planar surface, such as a window aperture. The linked program SPECPLOT that comes with SUNSPEC, can be used to plot solar spectral irradiance distributions. SUNSPEC can import solar position data created by SUNPATH and repeat its calculations for a sequence of times in the day and days in the year, outputting the results to its own output data files.

One option of SUNSPEC generates spectral solar radiation data files in the proper format for use in the WINDOW program developed at Lawrence Berkeley Laboratory and adopted by the National Fenestration Rating Council for rating window energy performance[5]. With this option, the user can determine accurately the solar heat gain coefficient of a fenestration system for any of a variety of atmospheric conditions, solar positions relative to the fenestration, wind speeds, and spectrally selective glazing systems in the WINDOW program's database.

The third program, AWNSHADE, calculates the unshaded fraction of a window's aperture area for any given sun position, relative to the window, for a variety of different exterior shading device geometries, including awnings, overhangs, and sidefins. It also calculates the effective unshaded fraction of a window for diffuse radiation from both the sky and reflected from the ground. It uses an isotropic sky model for the latter calculation. AWNSHADE can be used to generate a table of values for both direct beam and diffuse sky unshaded fraction, for use by other programs performing hourly window solar gain calculations or for other window performance analyses. AWNSHADE is useful for determining how much to reduce the solar heat gain predictions of WINDOW when a particular exterior shade geometry is added to the window.

Once preliminary selections of the placement, sizing, and glazing system have been made for the windows in a building, it is often desirable to determine the impact of the selection on annual energy performance. Numerous tools exist for making this determination. Most notable is the DOE-2 program developed at LBL. For residential fenestration systems another, simpler and easier to use, computer program called RESFEN is available for preliminary assessments of residential fenestration energy performance. Also developed at LBL, RESFEN is based on a large number of DOE-2 simulations, fitting performance curves to the results in such a way that the energy performances of cases in between those previously simulated can be estimated from the curve fits[6].

RESFEN estimates of the annual energy savings of one fenestration system compared to another, when installed in a prototypical residential building in any one of several cities in the U. S. Peak electrical load estimates are also made. The core calculational method used in RESFEN is due for a major improvement in the near future, as described by Crooks et.al.[7] A streamlined, especially fast, version of the DOE-2 building hourly annual energy performance simulation program, called "Power DOE", is scheduled to become the foundation of RESFEN. "This will enable accurate prediction of energy use and cost for any arbitrary window placement, size, type etc." according to a draft of Ref. 7. A companion program, called COMFEN, for use with nonresidential buildings is also planned. When completed, these programs will complete a package of tools that can be used for fenestration design, sizing, and energy performance prediction in a great variety of locations and for a variety of building types.

SUNPATH

SUNPATH calculates sun position at locations, dates, and times specified by the user. It outputs results to the screen as well as print and data files.

The times used by the program are both local standard time, called "civil time" and solar time, in which noon occurs when the sun is at its highest point in the sky each day. Most output files provide both solar and civil times for the solar positions given. Calculations for equal time intervals can be made using either type of time.

Output files generated by SUNPATH can be input to SUNSPEC, making it possible to run SUNSPEC for a sequence of solar positions automatically. SUNPATH can be used to determine the dates and times of day when the sun is near to a user-selected direction in the sky, for example in determining when the sun will shine down a tunnel or through a solar-aligned sculpture. Companion program PATHPLOT prepares a sunpath plot of solar altitude angle versus azimuth angle for one day in each month of a year, in either civil time or solar time. Hourline plots can also be included for each hour in the day in either solar time or civil time.

The program is currently MS-DOS based and does not require the presence of a graphics card or monitor. Without these, however, PATHPLOT graphic plots cannot be displayed. Either with or without graphics capability they can be printed or stored as plot instructions in either Hewlett Packard Graphics Language (HPGL) or Encapsulated Post Script (EPS) files. Many modern printers are able to read these languages and generate the desired plots directly from these output files.

The core algorithm for calculating sun position was written originally in FORTRAN by Dr. Joseph Michalsky of the Atmospheric Sciences Research Center of SUNY at Albany[8]. The core subroutine (which includes numerous corrections to the originally published model) calculates the local azimuth and elevation (altitude) angles of the sun at a specified location and time using an approximation to equations used to generate tables in an astronomical almanac. The basic equations are reputed to be accurate to 0.01 degree of angle. Atmospheric refraction correction is added, so the predicted sun position is the apparent position.

A sample line of screen output, with its column headers, for 1 January 1995 at 10 AM local standard time, as it appears on the screen, follows:

```
             CIVIL  CIVIL   |SOLAR  SOLAR   |SOLAR ALTITUDE     SOLAR AZIMUTH
 MO DA JUL HOUR   HR:MI:SE|HOUR   HR:MI:SE|DEGR DEG:MI:SEC    DEGR  DEG:MI:SEC
  1  1   1 10.00 10: 0: 0| 9.56   9:33:23|27.50 27°29'52'  141.74 141°44' 9''
```

Most of the entries on the above line are self-explanatory. "JUL" refers to the julian date, the number of days since 31 December of the previous year. Time (and angles) are given both in decimal form and in hours (degrees) minutes, and seconds form.

The user has three separate options for entering location data. A library of 233 locations, arranged alphabetically by place name, giving their latitudes, longitudes, and time zones is available.

The second choice is the user's own personal library of places, which can be added to, subtracted from, or modified during any run of the program.

Third is a default file that contains the location data used in the most recent run of the program.

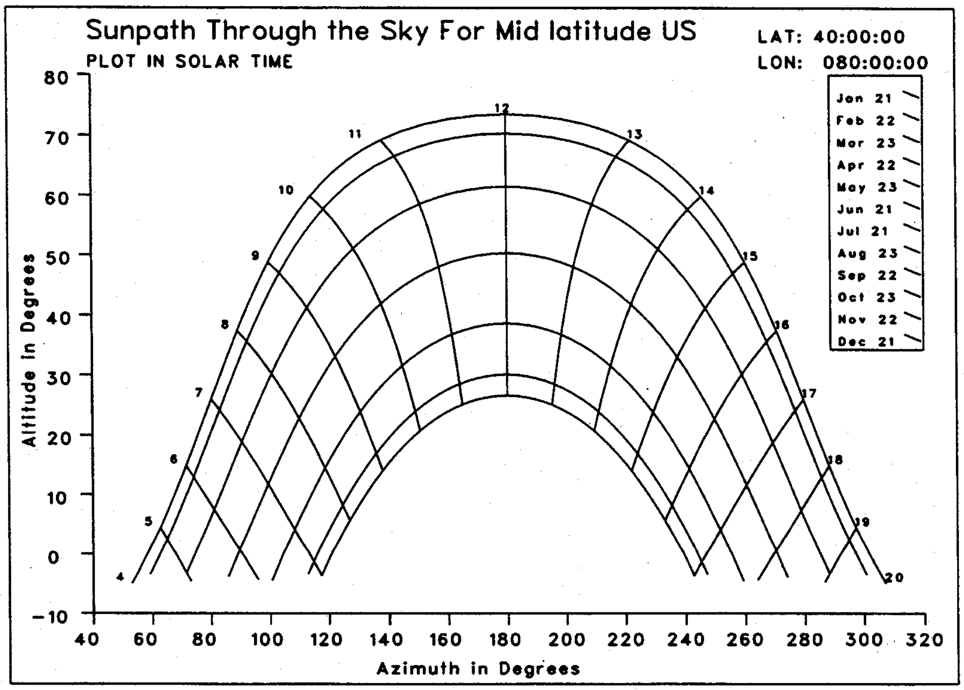

Figure 1. Solar time sunpath plot for 40 degrees north latitude

After the location has been selected a main menu screen is presented, giving the following options:

- Sun position for a single selected date and time
- Sun paths for a sequence of dates
- Year round timeline for a selected time
- Determining solstices and equinoxes
- Sunrise/Sunset times and daylength
- Dates and times for a given sun position
- Continuous readout of solar position
- Return to re-select the location
- Help
- Information about the program
- Information about local/solar conversions, twilight, and daylight saving time
- Calculate sunpaths and hourlines, exit SUNPATH, and run PATHPLOT
- Exit the program

With the exception of the last two of these, once a given option is completed, the user is returned to the main menu screen again for further selections. The first six selections above generate solar position data and place this on the screen and into a print file. The file continues to grow, as different options are selected from the main menu, until the program is exited. The resulting print file thus contains a log of the session. With this option a very large amount of information can be placed into this ASCII print file for printing, viewing on screen, or importing into a word processing program.

Each of the above choices leads the user into separate routines to perform the tasks indicated. Results are generally printed to the screen and to the print file. Data are also sent to an ASCII data file containing seven header lines followed by four columns of data, with azimuth angles, altitude angles, civil time, and solar time. These files can be imported into other software for preparing plots of the solar positions.

Companion program PATHPLOT, which can be invoked from within SUNPATH or run separately, reads these data files and prepares plots of the generated coordinates on an altitude versus azimuth angle graph. Figure 1 shows an example of the HPGL version of this output for a mid-latitude location in the U. S., and with times given in solar time. Azimuth angles are measured from north toward the east (at 90 degrees) to south (at 180 degrees).

The civil time plot of Figure 2, in contrast, shows the distorted "figure eight" shape of the hourlines on civil time plots. This illustrates graphically the difference between civil and solar times. The plots shown in Figures 1 and 2 are from the Beta version of PATHPLOT, available at this writing, and the line types used to distinguish between sunpaths for the different dates shown and, in Fig. 2, to distinguish the two different halves of a year in the hourlines, were not yet implemented. The different lines have different screen colors on computers equipped with color graphics monitors. The line type problem will be corrected in the final release of PATHPLOT.

Sunpath charts such as those shown in Figs. 1 and 2 can be very helpful in the placement and shading of windows.

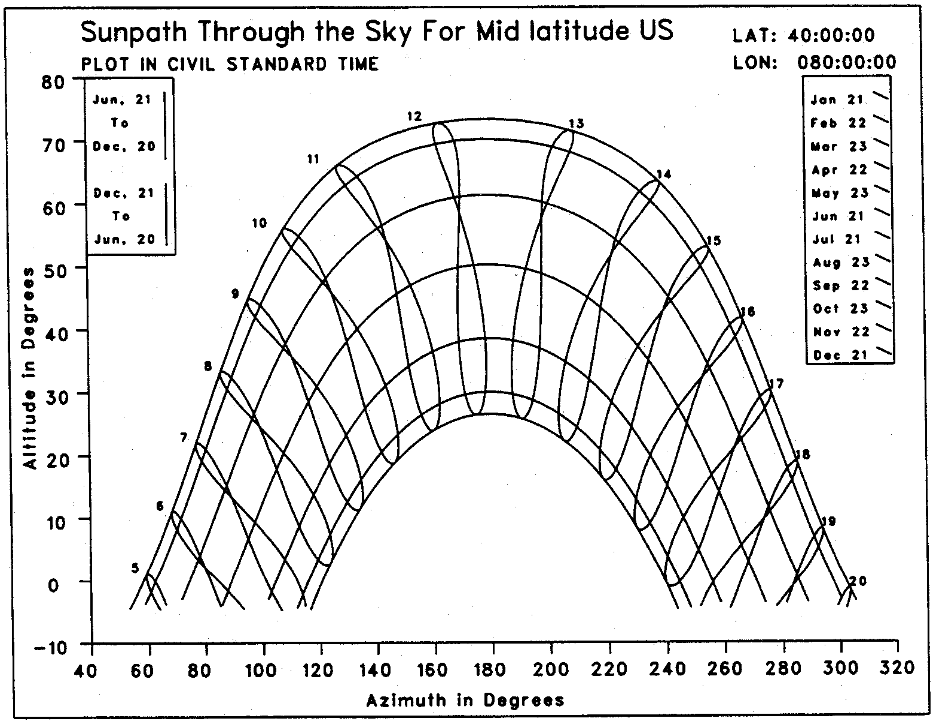

Figure 2. Civil time sunpath plot for 40 degrees north latitude.

SUNSPEC

SUNSPEC calculates cloudless sky solar spectral irradiances from the direct beam, diffuse sky, and ground reflections falling on an arbitrarily oriented plane, for user-selected atmospheric conditions and solar position. These spectral irradiance values extend over the wavelength range from 291 to 3987 nm in unequal intervals using one of three different extraterrestrial solar spectra. First is a NASA solar spectrum containing 114 wavelengths chosen to match the ones specified in ASTM standard E-490[9]. Second is a 1981 World Radiation Center (WRC) standard extraterrestrial spectrum, with 123 wavelengths, intended for use with LBL's Window 4.0 program as well as to match the extraterrestrial spectrum behind the terrestrial spectra provided in ASTM standards E891[10] and E892[11]. Last is a WRC 1985 standard spectrum containing 545 wavelengths. The last has the highest spectral resolution.

The program also calculates the broad-band total solar irradiances and illuminances corresponding to the spectral irradiances generated by the program, as well as luminous efficacies for each irradiance/illuminance pair. The program can accept multiple sun position files from SUNPATH and repeat its calculations for each sun position in the data file. An algorithm forming the core of the program, called SMARTS1, was developed by Gueymard[12]. The latest version, SMARTS2, was recently compared with several other computer programs intended for solar spectral irradiance calculations[13]. The next version of SUNSPEC will contain the latest version of the SMARTS algorithm.

When SUNSPEC is run, a list of 11 different atmospheric parameters files is shown, representing atmospheric conditions in three regions of the U.S. (northern, southeastern, southwest mountain) and for three seasons of the year (winter, spring, summer). Included also are a special atmosphere that generates a spectral distribution closely approximating ASTM standards E-891 and E-892 and an option for loading previously saved files of atmospheric parameter input data. It is anticipated that this list of different atmospheres will be changed and expanded if the SMARTS2 procedure is adopted by ASHRAE. This will ensure that an incident irradiance spectrum will be calculated that is appropriate for the location and atmospheric conditions where a fenestration system being designed is to be located.

If the user selects the WRC-81 extraterrestrial spectrum option, an output spectral data file is produced that can be read by WINDOW, if the user moves it to the appropriate WINDOW subdirectory and changes the name of the file to the one needed by WINDOW. If this spectrum is for a non-normal direction of incidence, then WINDOW 4.1 should be run for the correct angle of incidence as well.

Once an atmospheric conditions file is selected, the data from that file is loaded into the program and displayed on the screen, ready for use, or for editing to different values. This makes it fairly easy to generate multiple atmospheric condition files having only small changes from each other. The parameters included in the atmospheric condition files include Angström turbidity coefficients, turbidity at 500 nm, the quantity of precipitable water along a vertical path through the atmosphere, the surface atmospheric pressure, and the ozone abundance. In addition to these atmospheric parameters, additional parameters are also loaded from the input file. These include the local ground albedo (for calculating the ground-reflected radiation reaching tilted planes), the average surrounding area albedo (for atmospheric backscattering calculations), the solar constant (extraterrestrial total solar irradiance), and an earth orbit radius correction factor. Solar altitude and azimuth angle inputs are chosen as are names for saving the input data into a file if it has been modified, for the output print file, and for output data files.

The program calculates and outputs to a data file with one column giving the wavelengths and additional columns for each of the following spectral irradiances:

- Extraterrestrial
- Beam normal
- Beam tilted
- Sky diffuse tilted
- Beam horizontal
- Diffuse horizontal
- Global tilted
- Global horizontal
- Ground reflected tilted

These data are then integrated over wavelength both directly to give integrated irradiance values and weighted with the human photopic response function to give integrated illuminance values. A screen is then presented giving the input parameters used and the integrated broadband irradiances in W/m^2. These data are also written to the output print file. A second screen is then provided with the illuminances corresponding to the irradiances previously displayed and their ratio, which is the radiation luminous efficacy in lumens per Watt[14]. These incident solar irradiances can be used directly, or their corresponding spectral data files can be loaded into WINDOW 4.1 for accurate solar heat gain calculations.

AWNSHADE

AWNSHADE is a computer program for MS-DOS-based IBM and compatible personal computers. It calculates the unshaded fraction of a rectangular window of width W and height H for any given solar position relative to the window, when the window is shaded by an opaque awning with or without side walls and with or without opaque side fins.

It can also calculate the unshaded fraction for a sequence of such positions and output the results to a printer, a print file, and/or to files formatted for importing into graphic plotting programs. It calculates the effective unshaded fraction of diffuse sky radiation incident on the window, assuming uniform sky radiance/luminance. The effective unshaded fraction of ground-reflected radiation is

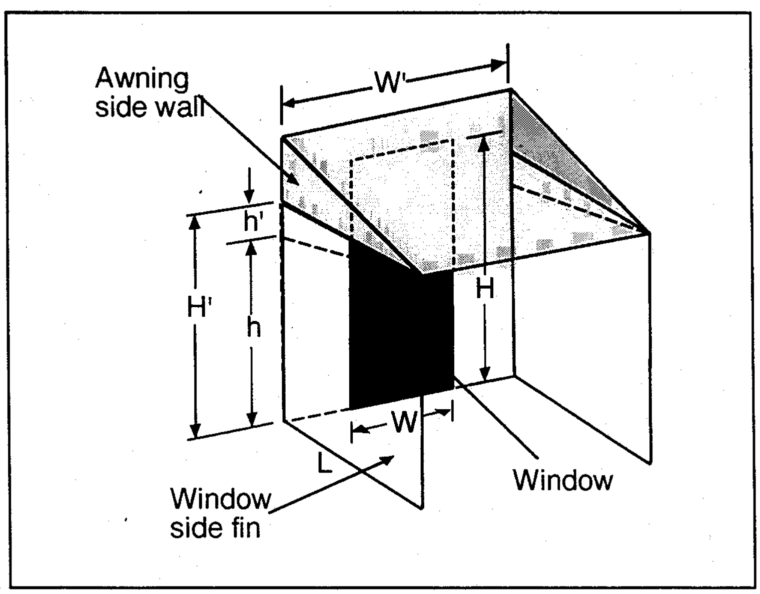

Figure 3. Illustration of awning of width W' above a window of width W with sidefins extending down to height H' above the window sill in the plane of the wall and to height h' at the front edge of the awning or side fins distance L from the wall.

also calculated.

The program includes a capability for handling cases in which shadows of the side of the awning/overhang cross the top of the window[3]. A new version includes an upgrade to include the case of a window, without an awning or overhang, shaded by vertical side fins only, or by an awning with side walls and side fins connected and extending down to the level of the window sill.

The relevant geometry and dimensions are illustrated in Fig. 3. A horizontal roof overhang can also be modelled, as a limiting case of the awning-only mode, in which dimension h' is zero and the height H' to the overhang is equal to or greater than the window height H. The width W' of the roof overhang can be arbitrarily large. In the side-fin-only case, the top edge of the side fins can be horizontal, when h'=0, or slanted, when H' $\geq$ h. To remove the sidewalls altogether, one sets H' > H and makes H' the height from the sill to the top of the awning.

AWNSHADE is written in Microsoft Visual BASIC for DOS version 1.0. A plot of the geometry and relevant dimensions is provided on screen with computers equipped with graphics capabilities. It is planned to add graphic plots of results on computers with graphics capabilities in the future.

It is also planned to add the capability of importing SUNPATH data files to permit automatically sequencing the program through a series of solar positions in order to calculate the time average of the unshaded fraction (for the direct sun component) of a window facing any azimuth over any time period desired. Adding an improved diffuse sky radiance/luminance angular distribution model is another planned addition to the program.

AWNSHADE has several output options. One may print out the single sun-direction results and/or a

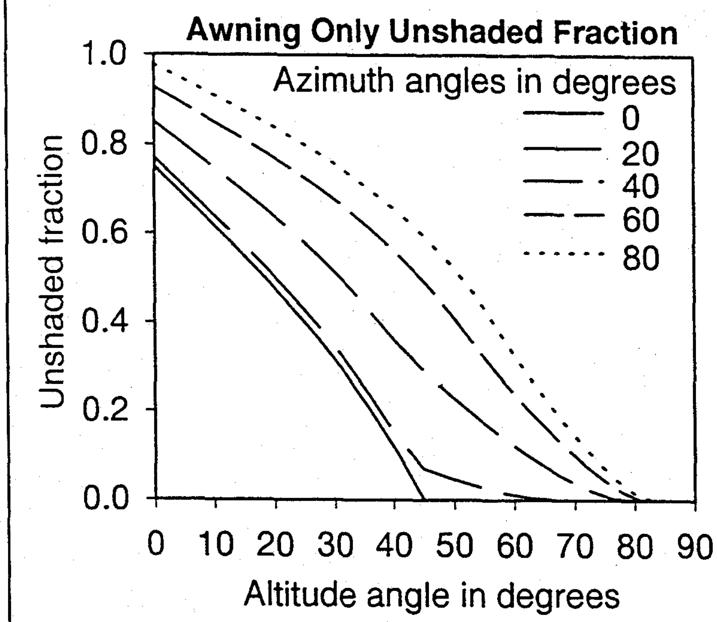

Figure 4. Awning only unshaded fraction for H = 4, W = 2, L = 3, h = 3, h' = 1, and W' = 3.

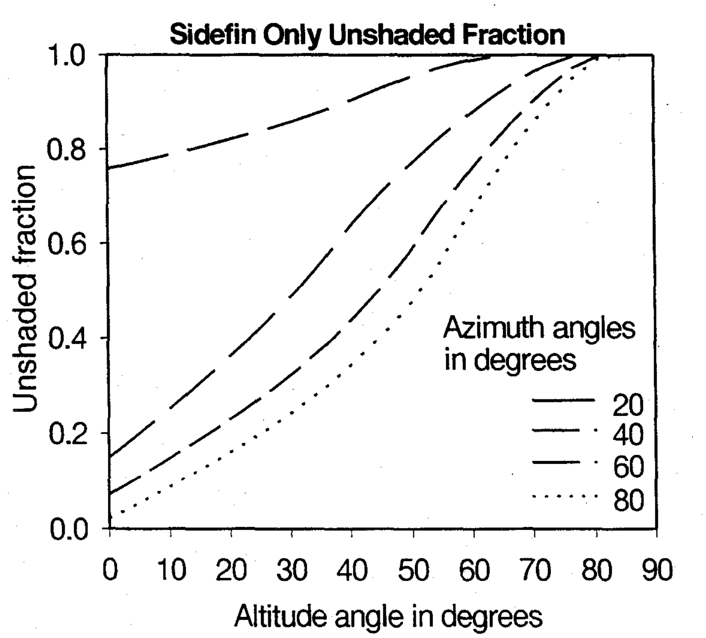

Figure 5. Sidefin only unshaded fraction for H = 4, W = 2, L = 3, h = 3, h' = 1, and W' = 3.

table of results for varying solar altitude and azimuth angles. This output can go either to the printer connected to port LPT1 or to a print file. Results may also be sent to data files for importing to plotting programs.

Figure 4 shows some sample output results for the case of a window that is 4 units high, 2 wide, covered by an awning extending out 3 from the wall, and with h = 3, h' = 1, and W' = 3 units.

Figure 5 is for the same window but with sidefins only attached to it. There is no awning or overhang, only vertical sidefins of height H' = h + h' = 4 at the wall and height h = 3 at distance L = 3 from it, the same dimensions as for the case shown in Figure 4.

It is clear that for an azimuth angle of zero degrees the unshaded fraction is 1.0 for all altitude angles with the sidefin only case. As the azimuth angle increases, the shading of the window with decreasing altitude angles becomes more pronounced.

CONCLUDING REMARKS

SUNPATH is a very user-friendly solar position calculation computer program. It contains a large number of computational options that should be of value in the process of energy-efficient building design and especially in the design, placement, and sizing of the building's fenestration systems. With this program a designer can prepare one or more sunpath charts tailored to the specific location of a planned building, the time zone in which it lies, and with the times of day shown on the chart in either solar time or local standard time.

Through careful use of the sunpath chart, the designer can determine the specific times of day and days in a year when the direct sun will shine through a window to a point in the room (by knowing the altitude and azimuth angle coordinates of the edges of the window relative to the point and plotting these on the sunpath chart directly). Points of interest in the room could include thermal mass intended to receive and store solar heat, objects of art that are to be kept away from direct solar radiation, and a variety of other targets of interest.

SUNSPEC is another user-friendly program that calculates the cloudless sky solar spectral irradiance. This solar spectral data is stored in a file for use by other programs and it is integrated to produce the total solar irradiance in W/m^2 incident on a window. The direct-beam radiation calculated by SUNSPEC can be imported into WINDOW 4.1 for accurate calculation of the solar radiant heat gain of a selected window when illuminated by a beam of solar radiation. SUNSPEC has an option that permits the user to repeat its calculations for a sequence of solar positions relative to the window and to save the resulting incident solar irradiances in a file or series of files. These can be used together with the solar heat gain coefficient of the window to estimate its direct beam solar gain for peak load and air conditioner sizing calculations. For spectrally selective glazing systems, where the shading coefficient method may produce inaccurate results, SUNSPEC spectral data files can be loaded into WINDOW 4.1 for more accurate calculations of the true solar heat gain coefficient for specific locations and their relevant seasonally variable atmospheric conditions.

AWNSHADE allows the user to determine reductions in computed solar heat gains resulting from partial shading of a window by exterior opaque awnings, roof overhangs, and side fins, either separately or in combination. The solar heat gain is calculated for an unshaded window and this value is multiplied by a factor, called the unshaded fraction (USF) calculated by AWNSHADE for the specific direction of incidence of direct beam solar radiation.

An approximate effective USF is calculated for the diffuse sky component of incident radiation using an isotropic sky radiance assumption. An effective USF for ground-reflected diffuse radiation is also calculated by the program and can be used to estimate the additional solar radiant gain from this contribution as well.

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REFERENCES

(1) McCluney, R., "Sunpath Version 1.1", Software Program and Operating Manual, Florida Solar Energy Center report FSEC-SW-2-93, Cape Canaveral, Florida, 4 March 1993.

(2) McCluney, R. and C. Gueymard, "Sunspec Version 1.0," Software Program and Operating Manual, Florida Solar Energy Center report FSEC-SW-3-93, Cape Canaveral, Florida, 4

March 1993. Gueymard, C., "Development and Performance Assessment of a Clear Sky Spectral Radiation Model," Solar '93, American Solar Energy Society Annual Conference, Washington, DC, April, 1993.

(3) McCluney, R., "Awning Shading Algorithm Update," ASHRAE Transactions, vol. 96, Part 1, 1990.

(4) Gueymard, C., "Updated Transmittance Functions for Use in Fast Spectral Direct Beam Irradiance Models," Proceedings, 23rd American Solar Energy Society Annual Conference, San Jose, CA, June 1994.

(5) Lawrence Berkeley Laboratory, Windows and Daylighting Group, "Window 4.1: A PC Program for Analyzing Window Thermal Performance in Accordance with Standard NFRC Procedures," Lawrence Berkeley Laboratory Report 35298, Berkeley, CA, 1994. Arasteh, D., M. S. Reilly, and M. Rubin, "A Versatile Procedure for Calculating Heat Transfer Through Fenestration Products," ASHRAE Transactions, Vol. 95, Part 2, 1989. Finlayson, E. U., D. Arasteh, C. Huizinga, M. Rubin, and M. S. Reilly, "Window 4.0: Documentation of Calculation Procedures," Lawrence Berkeley Laboratory Report 33943, Berkeley, CA, 1993.

(6) Sullivan, R., B. Chin, D. Arasteh, and S. Selkowitz, "RESFEN: A Residential Fenestration Performance Design Tool," ASHRAE Transactions, Vol. 98, Pt. 1, 1992. Also Lawrence Berkeley Laboratory Report LBL-31176.

(7) Crooks, B., et. al., "NFRC Efforts to Develop a Residential Fenestration Annual Energy Rating Methodology", Window Innovations Conference '95, 5-6 June 1995, Toronto, Ontario, Canada.

(8) Michalsky, J., *Solar Energy*, Vol. 90, No. 3, pp. 227-235 (1988). See also **The Astronomical Almanac**, available from the U. S. Government Printing Office, Washington, DC.

(9) ASTM E-490, "Standard Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables," American Society of Testing and Materials, 1916 Race St., Philadelphia, PA 19103. See also, Riordan, C., "Extraterrestrial Spectral Solar Irradiance Data for Modelling Spectral Solar Irradiance at the Earth's Surface," Report SERI/TR-215-2921, Solar Energy Research Institute (now National Renewable Energy Laboratory), 1617 Cole Blvd., Golden, CO 80401, 1987.

10) ASTM E-891, "Terrestrial Direct Normal Spectral Irradiance Tables for Air Mass 1.5," American Society of Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

(1 ASTM E-892, "Terrestrial Solar Spectral Irradiance Tables at Air Mass 1.5 for a 37° Tilted Surface," American Society of Testing and Materials, 1916 Race St., Philadelphia, PA 19103.

(12) Gueymard, C., "Development and Performance Assessment of a Clear Sky Spectral Radiation Model," Solar '93 -- 22nd ASES Conference, American Solar Energy Society, Washington, DC, April, 1993.

(13) Gueymard, C., "Critical Analysis and Performance Assessment of Clear Sky Solar Irradiance Models Using Theoretical and Measured Data," Solar Energy, Vol. 51, No. 2, pp. 121-138, 1993.

(14) McCluney, R., **Introduction to Radiometry and Photometry**, Artech House, Boston, 1994, p. 41.