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Atmospheric Renewable Energy Research, Volume 5 (Solar Radiation Flux Model)

by Clayton Walker and Gail Vaucher

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Computational and Information Sciences Directorate, ARL

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14. ABSTRACT This report documents a program coded in MATLAB, for renewable energy applications that was based on Ralph Shapiro's Solar Radiation Flux Model. Shapiro's approach was chosen based on its use of insitu-only measurement input. There exist numerous factors in the realm of solar radiation that limit the total amount of flux received at the ground level after traversing the atmosphere. The model encoded sought to simplify these variables and implement them into an algorithm to predict the net solar radiation flux received at ground level throughout the entire solar day. The model represents the atmosphere as a series of 3 homogeneous layers, and quantifies the effects on the vertical radiation in terms of reflectance, transmittance, and absorption. These 3 terms are a function of cloud type, thickness, and current atmospheric conditions. An introduction to the model's purpose, necessity, and development is detailed in Chapter 1. Chapter 2 describes Model equations and data tables, which are summarized in a model algorithm flowchart. A preliminary comparison between the model output and data sampled by an Atmospheric Renewable Energy Field Study #2 (ARE2) pyranometer during a clear sky day is provided in Chapter 3. Chapter 4 summarizes the model results and offers recommendations for future tactical energy unit independence applications.					
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Executive Summary

A Presidential Mandate in 2013 committed the Department of Defense (DoD) to converting at least 20% of its energy demand over to renewable energy sources by 2020, to include solar, wind, water, and geothermal. The Army also declared its intent on becoming a net-zero energy consumer by 2030. In order to accomplish these goals, renewable energy sources need to be integrated into existing electrical power control architecture. One method is to integrate renewable energy resources into the traditional tactical microgrids, creating hybrid microgrids. The challenge with such a task is the inconsistency in the power generated by renewable resources.

In order to create an effective and functioning hybrid microgrid, control algorithm is needed to regulate the amount of power coming into and going out of power grid components. For this high-level controller to work properly, it needs to quantify the amount of power produced by the renewable resource that will be available at the site, before the power is drawn off to its designated load. This problem can be abated with the implementation of an atmospheric model, such as a Solar Radiation Flux (SRF) Model. This report documents a program coded for renewable energy applications that was based on Ralph Shapiro's SRF Model, which was selected based on its use of insitu-only measurement input.

There are numerous factors that limit the total amount of solar radiation flux received at the ground level after traversing the atmosphere. The model documented in this report simplifies these variables and implements them in an algorithm that predicts the net solar radiation flux received at ground level throughout the entire solar day. The model represents the atmosphere as 3 homogeneous layers, and quantifies the effects on the vertical radiation in terms of reflectance, transmittance, and absorption. These 3 terms are a function of cloud type, thickness, and current atmospheric conditions.

The model's purpose, necessity, and development are detailed in Chapter 1. Chapter 2 describes the model equations and data tables, which are summarized in a model algorithm flowchart. A preliminary comparison between the model output and measured data sampled by Atmospheric Renewable Energy Field Study #2 (ARE2) pyranometers is provided in Chapter 3. Chapter 4 summarizes model results and provides recommendations for future tactical energy unit independence applications.

One recommendation for future model development is to create a stepwise function to facilitate the insertion of insitu meteorological observations throughout a single day. These perpetual and timely solar irradiance updates could yield a more accurate, dynamic model. With such a model, the isolated power grid controllers

would be well poised for exploiting and optimizing the atmospheric contributions to a hybrid power distribution.

1. Introduction

In 2013, a Presidential Mandate committed the DoD to convert at least 20% of its energy demand over to renewable energy sources by 2020, to include: solar, wind, water, and geothermal. Additionally, the Army is intent on becoming a net-zero energy consumer by 2030. In order to accomplish this, the Army needs to find a way to implement renewable energy sources into existing power control architecture. Solar generated power is one renewable energy resource that could be used to accomplish the Army's goals.

Integrating solar power into traditional isolated microgrids* is challenged by the variability of solar radiation fueling the power. While designing hardware alternatives into the grid configuration can counter this issue, for a relatively constant electrical power source one can also develop a model that will anticipate/predict the total amount of surface solar radiation flux. This solar radiation flux can then be combined with the total surface area of the solar energy sources, namely photovoltaic (PV) panels, to roughly determine the energy producing potential of an installation's solar array. The implicit advantage of using a predictive model is that it would also allow for an estimate of total energy that could be collected and stored over the entire day in order to more effectively ration the fossil fuel sources that the installation has available. The "ideal" model would be location-specific. Thus, it would be able to support utility/installation, microgrid, and tactical scale power resources.

1.1 The Challenge and Solution

The challenge with implementing renewable energy sources into traditional microgrids, making them "hybrid microgrids," is the inconsistency in the amount of power generated by the renewable resource. In order to create an effective and functioning hybrid microgrid, there needs to exist some form of control algorithm that regulates the amount of power coming into and going out of the power grid components. For this high-level controller to work properly, it needs to quantify the amount of power produced by the renewable resource, which for this research is solar, that will be available at the site before the power is drawn off to its designated load. This problem can be abated with the implementation of a model, such as a Solar Radiation Flux (SRF) Model. The SRF Model has the potential of providing atmospheric input that grid operators can use to accurately predict the net solar radiation flux received throughout the solar day after taking routine surface

* Microgrid is defined as "multiple power resources assembled as a single system (generator, storage, distribution and load), with the ability to run independently as an "island" and/or, as an integrated part of a larger grid."(Vaucher et al 2016)

meteorological observations, location information, and time information into account. The model chosen to answer the challenge was primarily based on work published by Ralph Shapiro (1982). The Shapiro SRF Model was selected due to its ability to use insitu-only measurements input. This report documents the results of translating Shapiro's written concepts into a computer code, along with several improvements to strengthen and retailor the code, in preparation for its renewable energy applications.

1.2 The Solar Radiation Flux Model

When one considers solar power as a relatively constant source, as the Sun will rise and set every day in most locations around the world, the concern then becomes quantifying the various effects that filter solar radiation flux before it reaches the ground. The model encoded represents these factors as the relative reflectance, transmittance, and absorption of atmospheric layers that will act on the solar radiation as it traverses strata. These terms are a function of cloud type, size, and density.

To create a practical computational environment in which enough data can be collected on each of the model's key terms, some aspects of the atmosphere and clouds must be standardized. Theoretically, the atmosphere can be divided into any number of descriptive layers with slightly different qualities in which different cloud types would reside. For the sake of simplicity, this model organizes the atmosphere into 3 homogeneous layers to mirror the general vertical atmospheric structure used by trained Sky Observers or Aerographers (Orvis et al. 1984). With the wide variation of cloud types and cloud microphysics, clouds are classified into 3 groups to populate the SRF Model: top-layer clouds (thick or thin cirrus, cirrostratus, cirrocumulus), mid-layer clouds (altostratus and altocumulus), and low-layer clouds (cumulus, cumulonimbus, and stratocumulus or stratus).

This information, when combined with the relative position of the Earth and Sun determined from site location and date, can be used to find the net solar radiation flux received at ground level. When propagated over an entire solar day, the irradiance takes on a Gaussian curve distribution that starts at the local sunrise and ends at the local sunset. The relatively stable results of the model appeared to match pyranometer solar radiation data collected under clear skies during the Atmospheric Renewable Energy Field Study #2 (ARE) at White Sands Missile Range, NM.

2. Procedure

In order to develop a programmable model, it was necessary to organize the model into components that could be coded into MATLAB: inputs, constants, functions, and outputs, as reflected in Fig. 1. After creating the algorithm flowchart based on Shapiro (1982), it became clear that the final output, solar radiation flux (X_3), was a product of 2 separable elements—the extraterrestrial radiation (X_0) and the coefficient of transmissivity due to atmospheric conditions (X_3). Extraterrestrial radiation is represented in Fig. 1 by the elements below the red line, and the coefficient of transmissivity is represented by the elements above the red line.

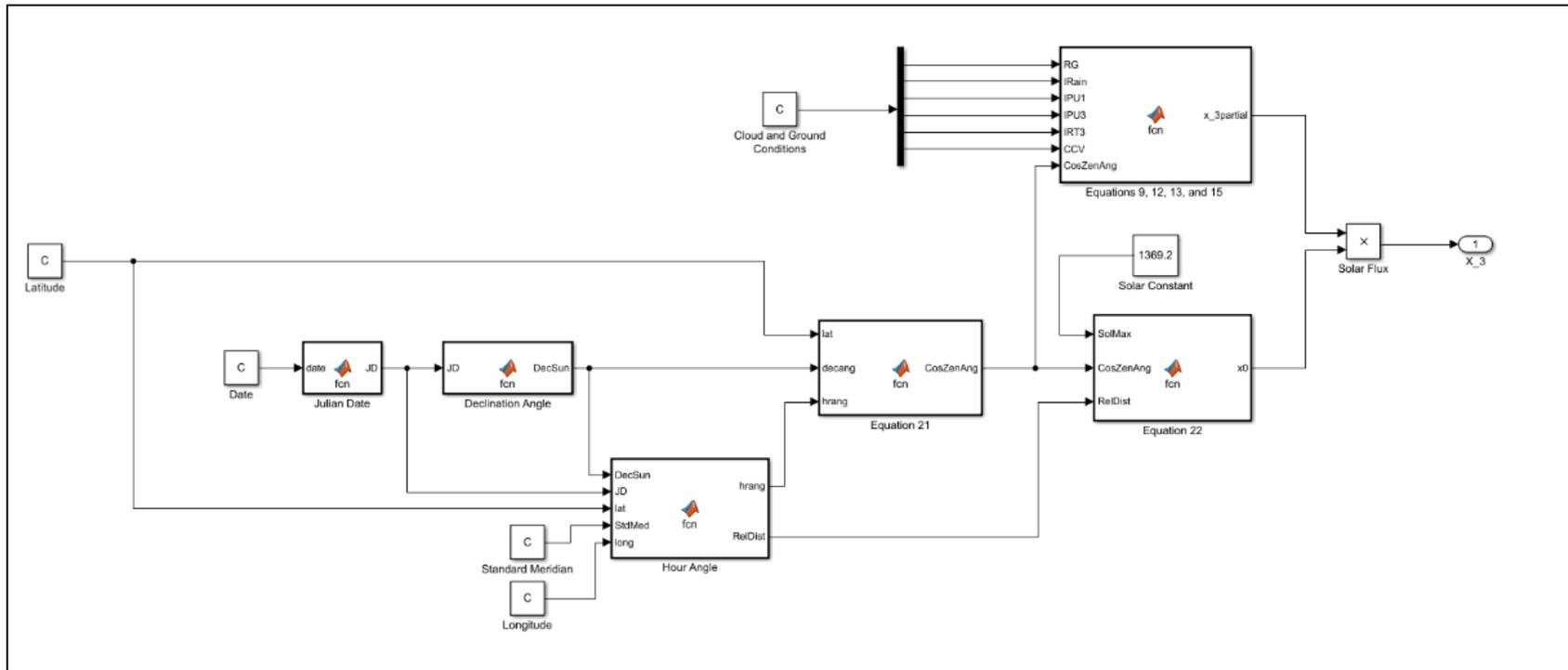


Fig. 1 Algorithm flowchart

2.1 Extraterrestrial Radiation

Extraterrestrial radiation, measured in W/m^2 , is a measure of the solar radiation received at the top of the atmosphere represented by Eq. 1. (Shapiro 1982)

$$X_0 = S \left(\frac{\bar{d}}{d}\right)^2 \cos(z) \quad (1)$$

Where S is the quiet Sun solar constant, $\left(\frac{\bar{d}}{d}\right)^2$ is a function of the ellipticity of the Earth's orbit and the position of the Earth in its orbit around the Sun represented by Eq. 2, and z is the zenith angle represented by Eq. 3. (Shapiro 1982) During minimum solar activity, S is roughly $1369.2 W/m^2$.

$$\left(\frac{\bar{d}}{d}\right)^2 = \left[1.000140 + 0.016726 \cos\left(\frac{2\pi(JD-2)}{day}\right)\right]^2 \quad (2)$$

JD is the local Julian Date, the number of days since January 1 to the current date, and day is the number of days in a year, which changes from 365 to 366 on leap years.

$$z = \arccos(\sin(\theta)\sin(\delta) + \cos(\theta)\cos(\delta)\cos(h)) \quad (3)$$

θ is the current latitude, δ is the declination angle described in Section 2.1.1, and h is the hour angle described in Section 2.1.2.

2.1.1 Declination Angle

Declination angle is the seasonal tilt of the Earth on its axis. This tilt affects the total amount of solar radiation received by certain locations. The process to calculate the declination angle is outlined in Eqs.4–13. (Meeus 1998)

$$JC = \frac{(\bar{JD} - 2451545)}{36525} \quad (4)$$

$$GML = \text{mod}\left(\frac{280.46646 + JC + (36000.76983 + 0.0003032JC)}{360}\right) \quad (5)$$

$$GMA = 357.52911 + JC(35999.05029 - 0.0001537 * JC) \quad (6)$$

$$EEO = 0.016708634 - JC(0.000042037 + 0.0000001267JC) \quad (7)$$

$$EOC = \sin(GMA)(1.914602 - JC(0.004817 + 0.000014JC) + \sin(2GMA)(0.019993 - 0.000101JC) + 0.000289\sin(3GMA)) \quad (8)$$

$$TL = GML + EOC \quad (9)$$

$$AppL = TL - 0.00569 - 0.00478\sin(125.04 - 1934.136JC) \quad (10)$$

$$MObl = 23 + \left(\frac{26 + \left(21.448 - \frac{JC(46.815 + JC(0.00059 - 0.001813JC))}{60} \right)}{60} \right) \quad (11)$$

$$OblCorr = MObl + 0.00256 \cos(125.04 - 1934.136JC) \quad (12)$$

$$\delta = \text{asin}(\sin(OblCorr)\sin(AppL)) \quad (13)$$

The absolute Julian Day ($\bar{J}D$) is a count of the number of days since noon on January 1, 1900 on the Gregorian calendar. Absolute Julian Day is converted into Julian Century (JC). The Geometric Mean Longitude of the Sun (GML) and Geometric Mean Anomaly (GMA) are used to calculate the position of a body in an elliptical orbit as a function of JC. Eccentric Earth Orbit (EEO) is a measure of the amount that Earth deviates from a perfect circle in its orbit about the Sun. Equation of Center of the Sun (EOC) is the angular difference between the position of a body in its elliptical orbit and the position it would occupy if motion were uniform. Sun's True Longitude (TL) is the ecliptic longitude at which an orbiting body could actually be found if its inclination were zero. Sun's Apparent Longitude (AppL) is corrected for apparent displacement of a celestial body based on the Earth's moving frame and the rocking motion that takes place about Earth's axis of rotation, as opposed to mean longitude. MObl and oblique correction (OblCorr) account for the angle at which the Earth is tilted, toward or away from the Sun depending on date, about its poles. (Meeus 1998)

2.1.2 Hour Angle

Hour angle (h) is a measure of the Sun's angle to the position of the observer starting at solar noon, 0° , and progressing in both directions by 15° per hour for the entire solar day. The angles are negative to the East, toward sunrise, and are positive to the West, toward sunset.

$$Y = \tan\left(\frac{OblCorr}{2}\right)^2 \quad (14)$$

$$EOT = 4(Y\sin(2GML) - 2EEO\sin(GMA) + 4EEO(Y)\sin(GMA)\cos(2GML) - 0.5Y^2\sin(4GML) - 1.25EEO^2\sin(2GMA)) \quad (15)$$

$$SRAng = \text{acos}\left(\frac{\cos(90.833)}{\cos(\theta)\cos(\delta)} - \tan(\theta)\tan(\delta)\right) \quad (16)$$

$$SN = \frac{(720 - 4long - EOT + 60tz)}{1440} \quad (17)$$

$$SR = SN - \frac{4SRang}{1440} \quad (18)$$

$$SS = SN + \frac{4SR_{ang}}{1440} \quad (19)$$

$$SL = 8SR \quad (20)$$

$$TST = mod\left(\frac{\frac{0.1(1440)}{24} + EOT + 4long - 60tz - 60}{1440}\right) \quad (21)$$

$$h = \frac{TST}{4} \pm 180 \quad (22)$$

The term Y is a placeholder for the modification of the oblique correction (OblCorr), which puts it in a form usable by equations going forward. The Equation of Time (EOT) is an adjustment to the clock based on the orbit of the Earth about the Sun during a single year. This term modifies the time of Solar Noon based on the JD. Sunrise Angle (SRAng) is the angle at which the Sun rises above the horizon. Solar Noon (SN) is when the Sun crosses the local standard meridian and is at the highest point in the sky. Sunrise (SR) and Sunset (SS) are the adjust times at which the Sun crosses the Eastern and Western horizons, respectively. Sunlight Length (SL) is the total duration or time the Sun is above the horizon. True Solar time (TST) is the time based on the apparent solar day. In the calculation of h , when TST is less than zero, then 180 is added.

2.2 Reflectivity, Transmissivity, and Absorption

Reflectivity, transmissivity, and absorption are the terms used to modify the extraterrestrial radiation into the amount actually received at ground level. The model code aligns with Shapiro's approach, by presuming that

$$R_k + T_k + A_k = 1, \quad (23)$$

Where R is reflectivity, T is transmissivity, A is absorption, and k is representative of the layer that is being calculated. A simple 2-stream approximation was then used, assuming that the radiative transport of solar flux only travels toward and away from the surface without a major scattering effect. Shapiro calculated mean climatological reflection and transmission coefficients using the National Climatic Data Center's hourly solar radiation and meteorological observations SOLMET data resource. His results describe the overall transmissivity and reflectivity of each atmospheric layer. The processed solar radiation assumptions are described using Eqs. 24 and 25, respectively (Shapiro 1982; SOLMET 1978). The equations serve to create a decimal value that represents the amount of solar radiation reflected or transmitted based on current atmospheric conditions.

$$R_k = \varphi_k \rho_k + (1 - \varphi_k) r_k \quad (24)$$

$$T_k = \varphi_k \tau_k + (1 - \varphi_k) t_k \quad (25)$$

Where φ is the a weighting coefficient expanded upon in Eq. 26 and 27, ρ is the overcast layer reflectivity coefficient calculated from Eq. 27, r is the clear layer reflectivity coefficient calculated by Eq. 27, τ is the overcast layer transmissivity coefficient calculated from Eq. 28, and t is the clear sky transmissivity coefficient calculated from Eq. 28.

$$\varphi_k = W f_k \quad (26)$$

$$W = C_0 + C_1 \cos z + C_2 f_k + C_3 f_k \cos z + C_4 \cos^2 z + C_5 f_k^2 \quad (27)$$

The weighting coefficient (φ_k) is a function of the fractional cloud coverage (f_k) per layer, a biquadratic polynomial function of weight (W) for each cloud type and fractional cloud coverage, and the solar zenith angle (z). The C series coefficients, shown in Table 1, are a result of Shapiro's observations and provide an adjusted measurement for each cloud type. In this way, both the overcast and clear conditions for each layer are taken into consideration in Eqs. 23 and 24 to determine the overall reflectance and transmission.

	C₀	C₁	C₂	C₃	C₄	C₅
Thin Ci/Cs	0.675	-3.432	1.929	.842	2.693	-1.354
Thick Ci/Cs	1.552	-1.957	-1.762	2.067	.448	.932
As/Ac	1.429	-1.207	-2.008	.853	.324	1.582
Sc/St	.858	-1.075	-.536	.750	.322	.501
Cu/Cb	2.165	-1.277	-3.785	2.089	-.387	2.342

Overcast and clear layer reflectivities are calculated with the same equation, Eq. 28, using "a" series coefficients (see Table 2) that are the result of Shapiro's observations. Here the F/K condition represents when there is fog or smoke present.

$$r_k \text{ or } \rho_k = a_0 + a_1 \cos \zeta + a_2 \cos^2 \zeta + a_3 \cos^3 \zeta \quad (28)$$

R_k	a₀	a₁	a₂	a₃
r ₁	.12395	-.34765	.39478	-.14627
r ₂	.15325	-.39620	.42095	-.14200
r ₃	.15946	-.42185	.48800	-.18493
r ₃ (F/K)	.27436	-.43132	.26920	-.00447
ρ ₁ (Thin)	.25674	-.18077	-.21961	.25272
ρ ₁ (Thick)	.60540	-.55142	-.23389	.43648
ρ ₂ (As/Ac)	.66152	-.14863	-.08193	.13442
ρ ₃ (Sc/St)	.67072	-.13805	-.10895	.09460
ρ ₃ (Cu/Cb)	.71214	-.15033	.00696	.03904

Overcast and clear layer transmissivities are calculated with, Eq. 29, using different “b” series coefficients that are the result of Shapiro’s observations (see Table 3).

$$t_k \text{ or } \tau_k = b_0 + b_1 \cos \zeta + b_2 \cos^2 \zeta + b_3 \cos^3 \zeta . \quad (29)$$

Table 3 “b” series coefficients (Shapiro 1982)

T_k	b₀	b₁	b₂	b₃
t ₁	.76977	.49407	-.44647	.11558
t ₂	.69318	.68227	-.64289	.17910
t ₃	.68679	.71012	-.71463	.22339
t ₃ (F/K)	.55336	.61511	-.29816	-.06663
τ ₁ (Thin)	.63547	.35229	.08709	-.22902
τ ₁ (Thick)	.26498	.66829	.24228	-.49357
τ ₂ (As/Ac)	.19085	.32817	-.08613	-.08197
τ ₃ (Sc/St)	.17960	.34855	-.14041	.00952
τ ₃ (Cu/Cb)	.13610	.29964	-.14875	.01962

There is one additional case in which the values of r, ρ, t, and τ are taken from a table, and not calculated by their respective equations. This special case occurs when the layer(s) above the layer being calculated are considered overcast, $f_{k-1} > 9/10$ ths. In this instance, the current layer is considered to be diffused, meaning that all radiative fluxes are no longer considered direct. As such, the relative reflectivity and transmissivity are taken from Table 4 in order to coincide with the difference in the amount of radiation allowed to enter each layer. The values in Table 4 are a result of Shapiro’s observations on the basis of increased path length as compared to a unit path length of the cosine of the zenith angle.

Table 4 Diffused coefficients (Shapiro 1982)

	Clear layer (r_k, t_k)	Overcast layer (ρ_k, τ_k)
R ₁
R ₂	.040	.560
R ₃	.045	.520 (Cu/Cb)
R ₃	.116 (F/K)	.609 (Sc/St)
T ₁
T ₂	.905	.361
T ₃	.900	.400 (Cu/Cb)
T ₃	.788 (F/K)	.311 (Sc/St)

Finally, the coefficient of transmissivity due to atmospheric conditions is calculated by Eq. 30, and multiplied with extraterrestrial radiation (X₀) to yield solar radiation flux at the ground level (X₃).

$$X_3 = T_1 T_2 T_3 / D_2 \quad (30)$$

$$D_2 = (1 - R_2 R_g) [(1 - R_1 R_2)(1 - R_2 R_3) - R_1 R_3 T_2^2] - R_g T_3^2 [(1 - R_1 R_2) R_2 + R_1 T_2^2] \quad (31)$$

In Eq. 31, R_g represents the relative albedo or reflectivity of the ground and foliage layer represented by a decimal.

A similar SRF Model developed by David Tofsted calculated the surface solar radiation flux for individual times throughout the day based on the atmospheric conditions and astronomical calculations (Tofsted 1993). This model followed a similar problem-solving process; however, the method used in this iteration to calculate declination angle and hour angle was slightly different in that it used equations from Jean Meeus’s “Astronomical Algorithms.” As such, an additional 0.8 was subtracted from X_3 , to compensate for the difference in approach.

3. Results

Results from the model developed were automatically plotted, as part of the SRF Model graphical user interface (GUI). In Fig. 2, the Surface Solar Radiation Flux output for a clear day is displayed.

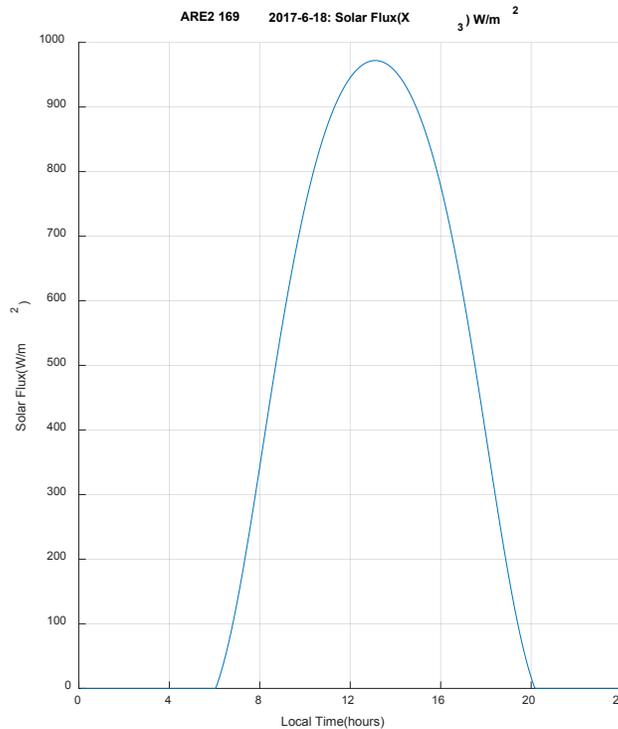


Fig. 2 Model prediction 2017 June 18

These data were visually compared to the sampled pyranometer data collected on the clear day of June 18, 2017 (See Fig. 3). Figure 3 displays the 2 pyranometer data time series extracted from the Atmospheric Renewable Energy Field Study #2 (ARE2) measurements. The West Pyranometer (blue) was orientated to view the sky from a zenith-facing angle. The East Pyranometer (red) was aligned with a PV Panel's south-facing (32 degrees) orientation. The higher magnitudes for the angled pyranometer reinforces the value of angling the PV Panel for increased solar radiation magnitudes.

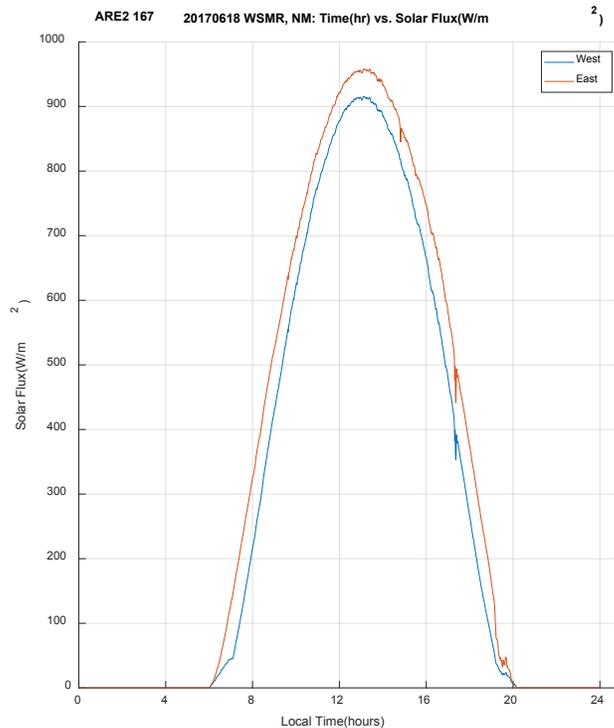


Fig. 3 Pyranometer data 170618

Both the SRF Model output and measured pyranometer data plots display a Gaussian-shaped curve distribution that begins at roughly 0600 hours Local Time (LT) and ends at a little past 2000 hours LT. The amplitudes of each rise up to approximately 970 W/m² at just past 1300 hours LT. Note that LT for the June data was Mountain Daylight Time (MDT), which explains the peak values being associated with 1300 LT, instead of the expected 1200 LT.

It can be reasonably asserted that the model output aligns well with the measured values under clear atmospheric conditions. Moreover, the model appears to coincide with the East Pyranometer, which is oriented at the same angle as the solar

panel. This result indicates that there is no need to make an adjustment to the model to account for the difference in angle.

4. Discussion, Conclusion, and Recommendations

The initial SRF model based on Shapiro's model and coded/developed by David Tofsted, calculated the net solar radiation flux and solar radiation flux without scattering, for a single point in time. For this project, it was decided early on that the "updated" SRF Model version would be more useful if the solar radiation flux output was propagated throughout an entire solar day, and a GUI interface was developed to provide both a single point output and an all-day solar radiation flux plot. This strategy would more easily allow for a comparison between model results and sampled pyranometer data, thus, preparing for the model for its verification and validation phase. When advancing from a single time output to an entire day, it became clear that the solar radiation flux without scattering did not correspond to the expected Gaussian curve. Since the output did not seem to relate to the measured data and the goal was to employ relevant simplicity, this feature was removed from the updated SRF Model.

The model was not adjusted for daylight savings time, as evidenced by the roughly 1-h difference in solar noon, and a 2-h difference in sunset. Consequently, a correction of 60 min was included in the calculation of solar time. Through testing different dates, it was revealed that the original declination angle and hour angle calculations did not allow for adjustments of the time of year in the solar day. This prompted declination angle and hour angle equation changes from those algorithms used in Tofsted's code, to those from Jean Meeus's "Astronomical Algorithms" (see Section 2). With the equation changes, the model output aligned well with the available pyranometer data. Unfortunately, most measured solar radiation data available at the conclusion of this task, were for clear skies. To more strenuously test the developed code, a variety of sky conditions, such as those acquired in the latter part of ARE2, will need to be employed.

For future SRF Model development, it is recommended to develop a stepwise function to facilitate the insertion of insitu meteorological observations throughout a single day. These perpetual and timely solar irradiance updates could yield a more accurate, dynamic model. With such a model, the isolated power grid controllers would be well poised for exploiting and optimizing the atmospheric contributions to a hybrid power distribution.

5. References

- Meeus, Jean. Astronautical Algorithms. 2nd Edition. Richmond (VA): Willmann-Bell; 1998.
- [NOAA] NOAA Global Monitoring Division. General Solar Position Calculations. Asheville (NC). Earth Systems Research Laboratory; 2017. Mar 9 [accessed 2017 June 19]. <https://www.esrl.noaa.gov/gmd/grad/solcalc/solareqns.PDF>.
- Orvis W, Hale H, Suhmann, I. Aerographer's Mate Third Class (Observer). Pensacola (FL): Naval Education and Training Program Development Center; 1984. NACEDTRA 10369.
- Shapiro R. Solar Radiative Flux Calculations from Standard Surface Meteorological Observations. Air Force Geophysics Laboratory (MA): Air Force Systems Command; 1982 Mar. Report No.: AFGL-TR-82-0039. Chapters 3 and 5 22–24, 38–39.
- SOLMET. Hourly solar radiation – surface meteorological observations. Vol. 1 – User's Manual Vol. 2. Asheville (NC): National Climatic Data Center; 1978 Aug. Report No.: TD-9724.
- SOLMET. User's Manual – Hourly Solar Radiation – Surface Meteorological Observations Vol. 1. Asheville (NC): National Climatic Data Center; 1978. Report No.: TD-9724.
- SOLMET. Final Report – Hourly Solar Radiation – Surface Meteorological Observations Vol. 2. Asheville (NC): National Climatic Data Center; 1979. Report No.: TD-9724.
- Tofsted D. A surface energy budget model modifying heat flow by foliage effects. White Sands Missile Range (NM). Army Research Laboratory (US), 1993 Jul. Report No.: ARL-TR-60.
- Vaucher G. Atmospheric Renewable Energy Research, Volume 3: Solar-Power Microgrids and Atmospheric Influences. White Sands Missile Range (NM). Army Research Laboratory (US); 2016 Sept. Report No.: ARL-TR-7797.

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Appendix A. SolRadCalc Function

This appendix appears in its original form, without editorial change.

Approved for public release; distribution is unlimited.

```

function [Tspan, x3, SolRad0] = SolRadCalc(year, month, ...
    day, lat, long, tz, RG, IRain, IPU1, IPU3, IRT3, CCV)
%-----
%-----
% Function Title:      SolRadCalc.m
% Last Modification:   170627
% Code Author(s):     walker/Tofsted
% Function Purpose:    Compute the Net Downward Flux of Solar Irradiance
%                     at the Top of the Foliage Layer (i.e. take account
%                     of the Equivalent Surface Reflection)
%
% Inputs:
%   CosZenAng    Current Cosine of the Solar Zenith Angle
%   RG           Effective Reflectivity of the Surface (Alpha_E)
%   IRain        Precipitation Flag --> 0=No Precip, 1=Precip.
%   IPU1         Upper Layer Clouds --> 1=Thin,      2=Thick.   (Cirrus)
%               Middle Layer Clouds--> 1,Medium, always.   (Not Used)
%   IPU3         Lowest Layer Clouds--> 1=Sc/St,      2=Cu/Cb.   (IPU3)
%   IRT3         Fog/Smoke (Ground) --> 0=None,      1=Present. (IRT3)
%   CCV          Fractional Cloud Amounts in 3 Layers (1,2,3)
%               1=Highest layer, 2=Mid layer, 3=Low layer.

% Genesis of Current File:
%   Several Equations were drawn from...
%       David Tofsted, 1993, "A Surface Energy Budget Model Modifying Heat
%       Flow by Foliage Effects," ARL-TR-60,
%       US Army Research Laboratory, White Sands Missile Range, NM,
%       88002-5501.
%       These will be denoted by [TR-60]

%   Several Equations were drawn from...
%       Ralph Shapiro, 1982, "Solar Radiative Flux Calculations From
%       Standard Surface Meteorological Observations," AFGL-TR-82-0039,
%       Air Force Geophysics Laboratory, Air Force Systems Command,
%       United States Air Force, Hanscom AFB, MA, 01731
%       These will be denoted by [TR-82]

%   Several Equations were drawn from...
%       Jean Meeus, 1999, "Astronomical Algorithms," ISBN 0-943396-61-1
%       These will be denoted by [ISBN - JM]
%-----
% Calculate the cosine of the zenith angle, CosZenAng, the extraterrestrial
% radiation per unit horizontal surface, X0, and the solar energy
% constant for a quiet Sun, S0.
[X0, S0, CosZenAng, Tspan, JD] = SolarInfo(year, month, day, lat, ...
    long, tz);

%-----
% Calculate a modified X_3, that will affect the solar radiation received at
% ground level as a Cloud Transmission Factor and the product of the
% transmissivities of each cloud layer, Tran_Direct
[X_3,Tran_Direct] = CloudTranmulti(CosZenAng, RG, IRain, IPU1, IPU3, ...
    IRT3, CCV);

```

```

%-----
% Calculate the net solar flux at ground level, x3, and
% display the solar radiation received at the start of the atmosphere,
% SolRad0 [TR-60]
x3 = X_3.*X0;
SolRad0 = S0*ones(1, 250);

%-----
% Plot the data
plot(TSpan, x3, TSpan, SolRad0)
ti = sprintf('ARE2 %d _ %d-%d-%d: Solar Flux(X_3) w/m^2', JD, year, ...
    month, day);
title(ti)
xlabel('Local Time(hours)', 'FontSize', 18)
xticks(0:2/24:1)
xticklabels({'0','2','4','6','8','10','12','14','16','18','20','22','24'})
ylabel('Solar Flux(w/m^2)', 'FontSize', 18)
yticks(0:100:1500)
legend('Solar Flux(Net)', ...
    'Solar Constant(Quiet Sun)', ...
    'location', 'northoutside')
grid on

```

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Appendix B. SolarInfo Function

This appendix appears in its original form, without editorial change.

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```

function [X0, S0, CosZenAng, time, J] = SolarInfo(year, month, day, lat, ...
    long, tz)
%-----
%-----
% Function Title:      SolarInfo.m
% Last Modification:   170627
% Code Author(s):      walker/Tofsted
% Function Purpose:    Compute the extraterrestrial radiation per unit
%                      horizontal surface, X0, and the components used to
%                      calculate it, S0 and CosZenAng, as shown in
%                      Equation 22 of the Shapiro Model.
% Inputs:
%   lat      Local latitude in degrees
%   long     Local longitude in degrees
%   year     Year(YYYY)
%   month    Month(MM)
%   day     Date(DD)
%   tz      Time Zone(+ or -)
%-----
%Calculate the local Julian Date based on user input
[J, leap] = JulianDate(year, month, day);

%-----
%Calculate the number of days since January 1st, 1900 to get to the actual
% Julian Day
datemod = year - 1900;
date = 0;
for i = 0 : datemod - 1
    if mod(i,4) == 0
        date = date + 366;
    else
        date = date + 365;
    end
end
datenum = date + J;

%-----
%Set up a scaled time array for 24 hour period, incrementing by 0.1/24
time = zeros(1, 250);
time(1) = 0.1/24;
for i = 2 : 250
    time(i) = round(time(i - 1) + (0.1/24),3);
    time(i - 1) = round(time(i - 1), 3);
end

%-----
%Using Equation 23 of the Shapiro model  $(d'/d)^2$ , a function of the
% ellipticity of the Earth's orbit and the position of the Earth in its
% orbit around the Sun, is calculated for the current Julian Date. This
% variable is saved as RelDist.
RelDist = 1.000140 + 0.016726*cos((2*pi*(J - 2))/day);

%-----

```

```

%Calculate the absolute Julian Day, JD, as a function of local Julian Date
% and the scaled time array. Convert Julian Day into Julian Century, JC.
% The Geometric Mean Longitude of the Sun, GMLSun, and Geometric Mean
% Anomaly, GMASun, are used to calculate the position of a body in an
% elliptical orbit as a function of Julian Century. Eccentric Earth
% Orbit, EEO, is a measure of the amount that Earth deviates from a
% perfect circle in its orbit. Equation of Center of the Sun, EOC, is the
% angular difference between the actual position of a body in its
% elliptical orbit and the position it would occupy if its motion were
% uniform. Sun's True Longitude, TLSun, is the ecliptic longitude at
% which an orbiting body could actually be found if its inclination were
% zero. Sun's Apparent Longitude, AppLSun, is corrected for aberration
% and nutation as opposed to mean longitude. MOblEq and OblCorr account
% for the angle at which the Earth is tilted, toward or away from the Sun
% depending on date, about its poles. [ISBN - JM]
for i = 1 : 250
    JD(i) = datenum + 2415018.5 + time(i) - tz/24;
    JC(i) = (JD(i) - 2451545)/36525;
    GMLSun(i) = mod(280.46646 + JC(i)*(36000.76983 + JC(i)*0.0003032),360);
    GMASun(i) = 357.52911 + JC(i)*(35999.05029 - 0.0001537*JC(i));
    EEO(i) = 0.016708634 - JC(i)*(0.000042037 + 0.0000001267*JC(i));
    EOC(i) = sin(deg2rad(GMASun(i)))*(1.914602 - JC(i)*(0.004817 + ...
        0.000014*JC(i))) + sin(deg2rad(2*GMASun(i)))*(0.019993 - ...
        0.000101*JC(i)) + sin(deg2rad(3*GMASun(i)))*0.000289;
    TLSun(i) = GMLSun(i) + EOC(i);
    AppLSun(i) = TLSun(i) - 0.00569 - 0.00478*sin(deg2rad(125.04 - ...
        1934.136*JC(i)));
    MOblEq(i) = 23 + (26 + ((21.448 - JC(i)*(46.815 + JC(i)*(0.00059 - ...
        JC(i)*0.001813))))/60)/60;
    OblCorr(i) = MOblEq(i) + 0.00256*cos(deg2rad(125.04 - ...
        1934.136*(JC(i))));
    DecSun(i) = rad2deg(asin(sin(deg2rad(OblCorr(i)))*...
        sin(deg2rad(AppLSun(i)))));
    Vary(i) = tan(deg2rad(OblCorr(i)/2))^2;
end

%-----
%The Equation of Time is a modification to the clock based on the orbit
% of the Earth about the Sun during a single year. It modifies the time
% of Solar Noon based on the Julian Date. Sunrise Angle, SunRiseAng, is
% the angle at which the sun rises. Solar Noon, SolNoon, is when the Sun
% transits the local celestial meridian and is at the highest point in
% the sky. SunRise and SunSet are the adjust times at which the Sun
% crosses the Eastern and western horizons respectively. Sunlight
% Duration, SunL, is the total time the Sun is above the horizon. True
% Solar time, SolTime, is the time based on the apparent solar day.
% [ISBN - JM]
for i = 1 : 250
    EOT(i) = 4*rad2deg(Vary(i)*sin(2*deg2rad(GMLSun(i))) - ...
        2*EEO(i)*sin(deg2rad(GMASun(i))) + ...
        4*EEO(i)*Vary(i)*sin(deg2rad(GMASun(i)))*...
        cos(2*deg2rad(GMLSun(i))) - ...
        0.5*Vary(i)*Vary(i)*sin(4*deg2rad(GMLSun(i))) - ...
        1.25*EEO(i)*EEO(i)*sin(2*deg2rad(GMASun(i))));
end

```

```

SunRiseAng(i) = rad2deg(acos(cos(deg2rad(90.833))/(cos(deg2rad(lat))*...
    cos(deg2rad(DecSun(i)))) - tan(deg2rad(lat))*...
    tan(deg2rad(DecSun(i)))));
SolNoon(i) = (720 - 4*long - EOT(i) + tz*60)/1440;
SunRise(i) = SolNoon(i) - 4*SunRiseAng(i)/1440;
SunSet(i) = SolNoon(i) + 4*SunRiseAng(i)/1440;
SunL(i) = SunRise(i)*8;
SolTime(i) = mod(time(i)*1440 + EOT(i) + 4*long - 60*tz,1440);
end

%-----
%Hour angle, HrAng, is the angle associated with the Sun at a specific time
% and location. Negative angles here are before solar noon, and positive
% angles after solar noon. Cosine of Solar zenith, CosZenAng, angle based
% on Equation 21 of the Shapiro Model in radians. Additionally, filter
% data for times when the zenith angle remains 0, i.e. when the sun is
% not visible. [ISBN - JM]
for i = 1 : 250
    if SolTime(i)/4 < 0
        HrAng(i) = SolTime(i)/4 + 180;
    else
        HrAng(i) = SolTime(i)/4 - 180;
    end
    CosZenAng(i) = sin(deg2rad(lat))*sin(deg2rad(DecSun(i))) + ...
        cos(deg2rad(lat))*cos(deg2rad(DecSun(i)))*cos(deg2rad(HrAng(i)));
end

%-----
%The extraterrestrial radiation per unit horizontal surface, X0, is
% calculated with Equation 22 of the Shapiro Model, using the solar
% constant SolMax measured in W/m^2, the cosine of the solar zenith angle
% CosZenAng, and the function of the ellipticity of the Earth's orbit
% and the position of the Earth in its orbit around the Sun, RelDist.
% [TR-60]
SolMax = 1369.2;
S0 = SolMax*RelDist^2;
for i = 1 : 250
    if (CosZenAng(i) < 0)
        X0(i) = 0.0;
    else
        X0(i) = S0.*CosZenAng(i);
    end
end
end

```

Appendix C. CloudTranmulti Function

This appendix appears in its original form, without editorial change.

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```

function [X_3,Tran_Direct] = CloudTranmulti(CosZenAng, RG, IRain, IPU1, ...
    IPU3, IRT3, CCV)
%-----
%-----
% Function Title:      CloudTranmulti.m
% Last Modification:   170627
% Code Author(s):     walker/Tofsted
% Function Purpose:    Compute the solar radiation flux transmissivity
%                      coefficient based on atmospheric conditions, cloud
%                      type, cloud density, and fractional cloud coverage
%MODEL TAKEN FROM:
% RALPH SHAPIRO, 1982, "SOLAR RADIATIVE FLUX CALCULATIONS FROM STANDARD
% SURFACE METEOROLOGICAL OBSERVATIONS", AFGL-TR-82-0039. AIR FORCE
% GEOPHYSICS LABORATORY, HANSCOM AFB, MA 01731
%
% Inputs:
%   CosZenAng   Current Cosine of the Solar Zenith Angle
%   RG          Effective Reflectivity of the Surface (Alpha_E)
%   IRain       Precipitation Flag --> 0=No Precip, 1=Precip.
%   IPU1        Upper Layer Clouds --> 1=Thin,      2=Thick.   (Cirrus)
%               Middle Layer Clouds--> 1,Medium, always.   (Not Used)
%   IPU3        Lowest Layer Clouds--> 1=Sc/St,      2=Cu/Cb.   (IPU3)
%   IRT3        Fog/Smoke (Ground) --> 0=None,      1=Present. (IRT3)
%   CCV         Fractional Cloud Amounts in 3 Layers (1,2,3)
%               1=Highest layer, 2=Mid layer, 3=Low layer.
%-----
%Transcribe the fractional cloud coverage from the vector CCV. However, if
% it's raining(IRain = 1) then all cloud layers are treated as overcast.
% F(n) is the fractional cloud coverage per layer.
if IRain == 1
    F1 = 1.0;
    F2 = 1.0;
    F3 = 1.0;
else
    F1 = CCV(1);
    F2 = CCV(2);
    F3 = CCV(3);
end

%-----
%Use diffuse values for layer 2 (midlayer) when layer 1 (top layer)
% is overcast and it is thick cirrus. (Obtained by setting ID2 = 1)
if (F1 >= 0.875) && (IPU1 == 2)
    ID2 = 1;
else
    ID2 = 0;
end

%-----
%Use diffuse values for layer 3 (lowest layer) when either layer 1
% (top layer) or layer 2 (mid layer) is overcast.
% (Obtained by setting ID3 = 1).
if (ID2 == 1) || (F2 > 0.875)

```

```

ID3 = 1;
else
ID3 = 0;
end

%-----
% Reflectivity, Transmissivity, and weight Coefficients (Table 10 - 12)
%-----
%Tabulate the coefficient matrices, last two values for each variable in
% the a and b series are flipped to follow the trend of the data since
% there may have been a typo in the original model. c series variable do
% not change. [TR-82]
a0 = [0.12395, 0.15325, 0.15946, 0.27436, 0.25674, 0.60540, ...
      0.66152, 0.67072, 0.71214];
a1 = [-0.34765, -0.39620, -0.42185, -0.43132, -0.18077, -0.5142, ...
      -0.14863, -0.13805, -0.15033];
a2 = [0.39478, 0.42095, 0.48800, 0.26920, -0.21961, -0.23389, ...
      -0.08193, -0.10895, 0.00696];
a3 = [-0.14627, -0.14200, -0.18493, -0.00447, 0.25272, 0.43648, ...
      0.13442, 0.09460, 0.03904];
b0 = [0.76977, 0.69318, 0.68679, 0.55336, 0.63547, 0.26498, ...
      0.19085, 0.17960, 0.13610];
b1 = [0.49407, 0.68227, 0.71012, 0.61511, 0.35229, 0.66829, ...
      0.32817, 0.34855, 0.29964];
b2 = [-0.44647, -0.64289, -0.71463, -0.29816, 0.08709, 0.24228, ...
      -0.08613, -0.14875, -0.14041];
b3 = [0.11558, 0.17910, 0.22339, -0.06663, -0.22902, -0.49357, ...
      -0.08197, 0.01962, 0.00952];
c0 = [0.575, 1.552, 1.429, 0.858, 2.165];
c1 = [-3.432, -1.957, -1.207, -1.075, -1.277];
c2 = [1.929, -1.762, -2.008, -0.536, -3.785];
c3 = [0.842, 2.067, 0.853, 0.750, 2.089];
c4 = [2.693, 0.448, 0.324, 0.322, -0.387];
c5 = [-1.354, 0.932, 1.582, 0.501, 2.342];

%-----
% Compute Reflectivity and Transmissivity of Top Layer(1). [TR-82]
%-----
%r and t for the top layer(1) are not dependant on any other layers so they
% will always be calculated by the equations in Tables 10 and 11
for i = 1 : 250
r1(i) = a0(1) + a1(1)*CosZenAng(i) + a2(1)*(CosZenAng(i)^2) + ...
      a3(1)*(CosZenAng(i)^3);
t1(i) = b0(1) + b1(1)*CosZenAng(i) + b2(1)*(CosZenAng(i)^2) + ...
      b3(1)*(CosZenAng(i)^3);

%IPU1 = 1 when there are thin Ci clouds present
if IPU1 == 1
%Calculate Reflectivity, Transmittances, and weighting Factors for
% overcast conditions, i.e. F1 > 0.875, (Table 10-12)
rho1(i) = a0(5) + a1(5)*CosZenAng(i) + a2(5)*(CosZenAng(i)^2) + ...
      a3(5)*(CosZenAng(i)^3);
tau1(i) = b0(5) + b1(5)*CosZenAng(i) + b2(5)*(CosZenAng(i)^2) + ...
      b3(5)*(CosZenAng(i)^3);

```

```

w1(i) = c0(1) + c1(1)*CosZenAng(i) + c2(1)*F1 + ...
        c3(1)*F1*CosZenAng(i) + c4(1)*(CosZenAng(i)^2) + c5(1)*(F1^2);

%else IPU = 2 when there are thick Ci clouds present
else
    %Calculate Reflectivity, Transmittances, and Weighting Factors for
    % overcast conditions, i.e. F1 > 0.875, (Table 10-12)
    rho1(i) = a0(6) + a1(6)*CosZenAng(i) + a2(6)*(CosZenAng(i)^2) + ...
              a3(6)*(CosZenAng(i)^3);
    tau1(i) = b0(6) + b1(6)*CosZenAng(i) + b2(6)*(CosZenAng(i)^2) + ...
              b3(6)*(CosZenAng(i)^3);
    w1(i) = c0(2) + c1(2)*CosZenAng(i) + c2(2)*F1 + ...
            c3(2)*F1*CosZenAng(i) + c4(2)*(CosZenAng(i)^2) + c5(2)*(F1^2);
end
end

%-----
% Compute Reflectivity and Transmissivity of Middle Layer(2). [TR-82]
%-----
%Implies top layer(1) is overcast, need to use Diffuse Values for middle
% layer(2) found in Table 3 of Shapiro Model. Since middle layer(2) has
% only one cloud type, the same values are used for r, t, rho, and tau.
% In this case the weighting factor w will determine overall reflectivity
% and transmissivity based on the fractional cloud coverage F(k).
for i = 1 : 250
    if ID2 == 1
        r2(i) = 0.040;
        t2(i) = 0.905;
        rho2(i) = 0.560;
        tau2(i) = 0.361;
        w2(i) = c0(3) + c1(3)*CosZenAng(i) + c2(3)*F2 + ...
                c3(3)*F2*CosZenAng(i) + c4(3)*CosZenAng(i)^2 + c5(3)*F2^2;

        %ID2 = 0 implies that the middle layer(2) is not diffused
    else
        r2(i) = a0(2) + a1(2)*CosZenAng(i) + a2(2)*(CosZenAng(i)^2) + ...
                a3(2)*(CosZenAng(i)^3);
        t2(i) = b0(2) + b1(2)*CosZenAng(i) + b2(2)*(CosZenAng(i)^2) + ...
                b3(2)*(CosZenAng(i)^3);

        %Calculate Reflectivity, Transmissivity, and Weighting Factors for
        % overcast conditions, i.e. F2 > 0.875, (Table 10-12)
        rho2(i) = a0(7) + a1(7)*CosZenAng(i) + a2(7)*(CosZenAng(i)^2) + ...
                  a3(7)*(CosZenAng(i)^3);
        tau2(i) = b0(7) + b1(7)*CosZenAng(i) + b2(7)*(CosZenAng(i)^2) + ...
                  b3(7)*(CosZenAng(i)^3);
        w2(i) = c0(3) + c1(3)*CosZenAng(i) + c2(3)*F2 + ...
                c3(3)*F2*CosZenAng(i) + c4(3)*(CosZenAng(i)^2) + c5(3)*(F2^2);
    end
end

%-----
% Compute Reflectivity and Transmissivity of Bottom Layer(3). [TR-82]
%-----

```

```

%ID3 = 1 implies that either the top layer(1) or the middle layer(2) are
% overcast causing the bottom layer(3) to be diffused
for i = 1 : 250
    if ID3 == 1

        %IRT3 = 1 implies that there is fog/smoke present
        if IRT3 == 1
            r3(i) = 0.116;
            t3(i) = 0.788;

        %IRT3 = 0 implies that there is notfog/smoke present
        else
            r3(i) = 0.045;
            t3(i) = 0.900;
        end

        %IPU = 1 implies that there are Sc/St clouds present
        if IPU3 == 1
            rho3(i) = 0.609;
            tau3(i) = 0.311;
            w3(i) = c0(4) + c1(4)*CosZenAng(i) + c2(4)*F3 + ...
                c3(4)*F3*CosZenAng(i) + c4(4)*(CosZenAng(i)^2) + ...
                c5(4)*(F3^2);

        %IPU = 2 implies that there are Cu/Cb clouds present
        else
            rho3(i) = 0.520;
            tau3(i) = 0.400;
            w3(i) = c0(5) + c1(5)*CosZenAng(i) + c2(5)*F3 + ...
                c3(5)*F3*CosZenAng(i) + c4(5)*(CosZenAng(i)^2) + ...
                c5(5)*(F3^2);
        end

    %ID3 = 0 implies that the bottom layer(3) is not diffused
    else

        %IRT3 = 1 implies that there is fog/smoke present
        if IRT3 == 1
            r3(i) = a0(4) + a1(4)*CosZenAng(i) + ...
                a2(4)*(CosZenAng(i)^2) + a3(4)*(CosZenAng(i)^3);
            t3(i) = b0(4) + b1(4)*CosZenAng(i) + ...
                b2(4)*(CosZenAng(i)^2) + b3(4)*(CosZenAng(i)^3);

        %IRT3 = 0 implies that there is not fog/smoke present
        else
            r3(i) = a0(3) + a1(3)*CosZenAng(i) + ...
                a2(3)*(CosZenAng(i)^2) + a3(3)*(CosZenAng(i)^3);
            t3(i) = b0(3) + b1(3)*CosZenAng(i) + ...
                b2(3)*(CosZenAng(i)^2) + b3(3)*(CosZenAng(i)^3);
        end

        %IPU = 1 implies that there are Sc/St clouds present
        if IPU3 == 1
            rho3(i) = a0(8) + a1(8)*CosZenAng(i) + ...

```

```

        a2(8)*(CosZenAng(i)^2) + a3(8)*(CosZenAng(i)^3);
tau3(i) = b0(8) + b1(8)*CosZenAng(i) + ...
        b2(8)*(CosZenAng(i)^2) + b3(8)*(CosZenAng(i)^3);
w3(i) = c0(4) + c1(4)*CosZenAng(i) + c2(4)*F3 + ...
        c3(4)*F3*CosZenAng(i) + c4(4)*(CosZenAng(i)^2) + ...
        c5(4)*(F3^2);

%IPU = 2 implies that there are Cu/Cb clouds present
else
    rho3(i) = a0(9) + a1(9)*CosZenAng(i) + ...
        a2(9)*(CosZenAng(i)^2) + a3(9)*(CosZenAng(i)^3);
    tau3(i) = b0(9) + b1(9)*CosZenAng(i) + ...
        b2(9)*(CosZenAng(i)^2) + b3(9)*(CosZenAng(i)^3);
    w3(i) = c0(5) + c1(5)*CosZenAng(i) + c2(5)*F3 + ...
        c3(5)*F3*CosZenAng(i) + c4(5)*(CosZenAng(i)^2) + ...
        c5(5)*(F3^2);
end
end
end

%-----
% Weighting Functions, Equation 15 [TR-82]
%-----
%The weighting function value phi is rounded up to 1 if the fractional
% cloud coverage is greater than 95%, indicating that the layer is
% severely overcast. The clear sky portion of the reflectivity and
% transmissivity is ignored in this case.
for i = 1 : 250
    if (F1 > 0.95)
        phi1(i) = 1.0;
    else
        phi1(i) = w1(i)*F1;
    end

    if (F2 > 0.95)
        phi2(i) = 1.0;
    else
        phi2(i) = w2(i)*F2;
    end

    if (F3 > 0.95)
        phi3(i) = 1.0;
    else
        phi3(i) = w3(i)*F3;
    end
end

%-----
% Reflectivities and Transmissivities of the cloud layers,
% Equations 12 & 13 [TR-82]
%-----
%Tran_Direct is modified by reducing it by 0.09, this accounts for the
% different method used to find CosZenAng and HrAng
for i = 1 : 250

```

```

R1(i) = phi1(i)*rho1(i) + (1 - phi1(i))*r1(i);
T1(i) = phi1(i)*tau1(i) + (1 - phi1(i))*t1(i);
R2(i) = phi2(i)*rho2(i) + (1 - phi2(i))*r2(i);
T2(i) = phi2(i)*tau2(i) + (1 - phi2(i))*t2(i);
R3(i) = phi3(i)*rho3(i) + (1 - phi3(i))*r3(i);
T3(i) = phi3(i)*tau3(i) + (1 - phi3(i))*t3(i);

if CosZenAng(i) <= 0
    Tran_Direct(i) = 0;
else
    Tran_Direct(i) = T1(i)*T2(i)*T3(i);
end
end

%-----
% Total Solar Flux at ground level, Equation 9 [TR-82]
%-----
for i = 1 : 250
    d1(i) = 1.0 - R1(i)*R2(i);
    d2(i) = 1.0 - R2(i)*R3(i);
    d3(i) = 1.0 - R3(i)*RG;
    D1(i) = d1(i)*d2(i) - R1(i)*R3(i)*T2(i)^2;
    D2(i) = d3(i)*D1(i) - RG*(T3(i)^2)*(d1(i)*R2(i) + R1(i)*T2(i)^2);
    X_3(i) = (Tran_Direct(i)/D2(i))- 0.08;
end

```

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Appendix D. JulianDate Function

This appendix appears in its original form, without editorial change.

Approved for public release; distribution is unlimited.

```

function [JD, leap] = JulianDate(yyyy, mm, dd)
%-----
%-----
% Function Title:      JulianDate.m
% Last Modification:   170627
% Code Author(s):     walker/Tofsted
% Function Purpose:    Converts calander date into Julian Date and
%                     confirms or denies that it is a leap year.
%
% Inputs:
%     YYYY      Year
%     MM        Month
%     DD        Day
%-----
%Error check for date
if dd > 31
    error('Entered invalid date, check user input')
end

%-----
%Set default state to non-leap year to be modified on a positive
% check later in code
leap = 0;

%-----
%Assign a date number based on the current month entered with an
% embedded error code to check if a proper month was entered
switch mm
    case 1
        month = 0;
    case 2
        month = 0 + 31;
    case 3
        month = 0 + 31 + 28;
    case 4
        month = 0 + 31 + 28 + 31;
    case 5
        month = 0 + 31 + 28 + 31 + 30;
    case 6
        month = 0 + 31 + 28 + 31 + 30 + 31;
    case 7
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30;
    case 8
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30 + 31;
    case 9
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31;
    case 10
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30;
    case 11
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31;
    case 12
        month = 0 + 31 + 28 + 31 + 30 + 31 + 30 + 31 + 31 + 30 + 31 + 30;
    otherwise
        error('Entered invalid month, check user input');
end

```

```
end

%-----
%Julian dates are modified after January in the case of a leap year
% if both cases are positive here, the program treats the date as
% a leap year.
if (mm >= 2) && (mod(yyyy,4) == 0)
    leap = 1;
end

%-----
%Combine all calculated components of the date and return
JD = month + leap + dd;
```

List of Symbols, Abbreviations, and Acronyms

ARL	US Army Research Laboratory
ARE2	Atmospheric Renewable Energy Field Study #2
DoD	Department of Defense
EEO	Eccentric Earth Orbit
EOC	Equation of Center of the Sun
EOT	Equation of Time
f_k	fractional cloud coverage
GML	Geometric Mean Longitude of the Sun
h	Hour angle
JC	Julian Century
JD	local Julian Date
\overline{JD}	Julian Day
k	representative of the layer that is being calculated
LT	Local Time
MDT	Mountain Daylight Time
NWP	numerical weather prediction
OblCorr	Oblique correction
φ	weighting coefficient expanded upon
φ_k	weighting coefficient
ρ	Overcast
PV	photovoltaic
r	clear layer reflectivity coefficient calculated
R_g	relative albedo
ROTC	Reserved Officer's Training Corp
δ	declination angle
S	quiet Sun solar constant

SL	Sunlight Duration
SN	Solar Noon
SR	Sunrise
SRAng	Sunrise Angle
SRFM	Solar Radiation Flux Model
SS	Sunset
t	clear sky transmissivity coefficient calculated
τ	overcast layer transmissivity coefficient calculated
θ	current latitude,
TL	True Longitude
TST	True Solar time
W	bi-quadratic polynomial function
X_0	extraterrestrial radiation
X_3	radiation flux
X_3'	coefficient of transmissivity due to atmospheric conditions
Y	place holder for the modification of the oblique correction
Z	zenith angle

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IMAL HRA MAIL & RECORDS MGMT

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7 DIR ARL
(PDF) RDRL CIE D
C WALKER
G VAUCHER
C HOCUT
D KNAPP

(5 CD) RDRL CIE D
(5 HC) G VAUCHER
RDRL SED D
M BERMAN
D PORSCHE
S HU