USERS MANUAL TO THE FAST SOLAR/INFRARED RADIATIVE TRANSFER MODEL

VERSION 1.0

TOM GREENWALD (AWG PROXY DATA PROJECT MANAGER & SCIENCE LEAD)
ALLEN HUANG (AWG PROJECT PI)
JUSTIN SIEGLAFF
ERIK OLSON

COOPERATIVE INSTITUTE FOR METEOROLOGICAL SATELLITE STUDIES
UNIVERSITY OF WISCONSIN - MADISON

30 MAY 2008

LIST OF TABLES

LIST OF ACRONYMS

ABI	Advanced Baseline Imager
AIRS	Atmospheric Infrared Sounder
ATBD	Algorithm Theoretical Basis Document
AWG	Algorithm Working Group
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CRTM	Community Radiative Transfer Model
GEO	Geosynchronous Earth Orbit
GOES-R	Geostationary Operational Environmental Satellite R series
IR	Infra-Red
IRSSEM	Infrared Sea Surface Emissivity Model
LBL	Line by Line
LEO	Low Earth Orbit
MODIS	MODerate Resolution Imaging Spectroradiometer
NWP	Numerical Weather Prediction
netCDF	network Common Data Format
OPTRAN	Optical Path TRANsmittance
RTM	Radiative transfer model
SEVIRI	Spinning Enhanced Visible Infra-Red Imager
SOI	Successive Order of Interaction
SRF	Spectral response function
SSEC	Space Science and Engineering Center
TOA	Top of Atmosphere
WRF	Weather Research and Forecasting

1 Introduction

1.1 *Purpose*

The purpose of this manual is to familiarize users with the fast solar/infrared forward RTM developed at CIMSS for GOES-R AWG Proxy Data activities. Specifically, the manual will enable the user to understand most aspects of the forward RTM and to run the code for producing TOA radiances for all ABI bands, as well as many other satellite sensors, from 3D NWP model output.

1.2 *Who Should Use This Manual?*

This manual is intended for members of the GOES-R AWG who will use simulated ABI radiance datasets for testing algorithms and products.

1.3 *Section Summaries*

The next section provides a summary of the fast solar/IR forward RTM and includes a brief history of its development. Section 3 describes in detail the fast model code and its associated data sets and shows how to set up and execute the code.

2 Fast Model Overview

2.1 *Requirements*

The goal of the Proxy Data project is the creation and distribution of both simulated and observationally derived datasets to support the AWG. The requirements for this project are coupled to the ongoing GOES-R Risk Reduction efforts at CIMSS from which the software tools and databases used in the current effort were initially developed. Elements of the Proxy Data requirements relevant to the forward RTM include

- Simulation of ABI measurements
- Enhancements of the fast forward model
- Development of cloud property databases
- Production of land surface IR emissivity and albedo databases

2.2 *Development and Implementation Team*

The following is a list of the team members and their roles:

Dr. Tom Greenwald
CIMSS, University of Wisconsin
Proxy Data program manager
Science team lead

tomg@ssec.wisc.edu
Tel: 608-263-3629

Dr. Hung-Lung (Allen) Huang
CIMSS, University of Wisconsin
AWG Principal Investigator
allenh@ssec.wisc.edu
Tel: 608-263-5283

Dr. Ping Yang
Department of Atmospheric Sciences, Texas A&M University
Radiative transfer model support
pyang@ariel.met.tamu.edu
Tel: 979-845-4923

Erik Olson
CIMSS, University of Wisconsin
Implementation, optimization and testing
eriko@ssec.wisc.edu
Tel: 608-262-9538

Justin Sieglaff
CIMSS, University of Wisconsin
Implementation
justins@ssec.wisc.edu
Tel: 608-265-5357

Dr. Bryan Baum
SSEC, University of Wisconsin
Cloud optical properties support
Bryan.Baum@ssec.wisc.edu
Tel: 608-263-3898

2.3 *Algorithm*

The fast solar/IR RTM is more than a single model. It is actually a complex forward model system composed of many parts. These parts include models to compute the optical depth due to gases at each layer of the atmosphere, models and databases to specify surface radiative and cloud scattering properties, as well as the method used to solve the radiative transfer equation for solar and IR radiances at the TOA.

Different band models are used to estimate layer gas optical depths depending on the spectral region. At solar wavelengths (ABI bands 1-7; see Table 1), a lookup table approach is implemented. Layer atmospheric transmittances were computed from LBL calculations across a given instrument band for 8 different gases (H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2, and N_2) as functions of the layer pressure, layer temperature, and the layer vertical gas density over a wide range of atmospheric conditions. These calculations were then convolved across the instrument band while taking into account the instrument SRF to provide band-averaged transmittances. A multidimensional lookup table was produced from these calculations, from which the band-averaged transmittances are interpolated. The accuracy of the total transmittances is typically under 0.01% for all bands except ABI band 4, which increases to about 0.4%, but only because the atmospheric transmission is extremely small, on the order of 10^{-9}. One known drawback of the method is that, for simplicity, the attenuation of the direct solar beam and of the diffuse solar radiation by gases across a given instrument band is assumed the same. Strictly speaking, the attenuation will be different owing to the different spectral behavior of the radiation across the instrument band.

At IR wavelengths (ABI bands 8-16) the well-known OPTRAN approach is used (McMillin et al. 1995). OPTRAN is a statistical regression-type band model that predicts the polychromatic optical depth across an instrument band due to gases (currently limited to water vapor, O_3, and "dry") for each atmospheric layer. The statistical predictors are functions of temperature, pressure, zenith angle, and absorber amount. A variant of OPTRAN used here is called Compact-OPTRAN, which is available within CRTM. It differs mainly from traditional OPTRAN in that fewer predictors are used. The accuracy of Compact-OPTRAN is not known; however, OPTRAN is usually within 0.2 K for much of the IR spectrum. In practice, the band models (both solar and IR) use not only information at the WRF model native levels but also require additional information above the model top (typically 50 hPa) since absorption by gases in the stratosphere, e.g., O_3, are important at certain bands. This additional information is in the form of climatic profiles of temperature, water vapor mixing ratio, and O_3 concentration.

Another important part of the fast solar/IR RTM is assigning single-scattering properties (extinction efficiency, single-scatter albedo, scattering phase function) to each of the hydrometeor species produced by the WRF model. Five different species are predicted: cloud liquid, cloud ice, rain, snow, and graupel. For hydrometeors composed of ice (whose properties are assumed the same) the single-scattering properties derived in Baum et al. (2005a; 2005b) are used, which utilized a large collection of in situ observations of ice clouds from many field campaigns in the midlatitudes and tropics (http://www.ssec.wisc.edu/~baum/Cirrus/IceCloudModels.html). The advantages of these databases are that there is no need to artificially classify scattering properties by cloud type or region and more importantly, the ice particle scattering properties will be consistent with field measurements. Because detailed phase function information is used in the RTM, Legendre polynomial expansion terms were also generated from the scattering phase functions provided by Baum et al. For the solar bands all of the single-scattering properties were averaged over each band using the instrument SRF. In the IR, however, only the properties at the central wavelength were used. The original spectral resolution (1 cm^{-1} from 100-3250 cm^{-1}) was maintained in this case since the IR RTM is also used to simulate spectra from AIRS and other IR hyperspectral instruments. For liquid hydrometeors (cloud and rain), Lorenz-Mie calculations were performed for the same spectral resolution and ranges as the ice properties, and the same spectral averaging was used. All of these databases were subsequently organized into tabular form as functions of extinction efficiency and hydrometer effective diameter (a quantity diagnosed in the WRF model.) Details concerning these lookup tables are provided in Section 3.2.3.

The next component is the assignment of surface radiative properties (albedo and emissivity) for land and water. Over land, static databases are used. In the solar bands the Filled Land Surface Albedo Product developed by the MODIS atmosphere science team (http://modis-atmos.gsfc.nasa.gov/ALBEDO/index.html.) Although not all of the ABI solar bands have closely corresponding MODIS bands (see Table 2), no attempt was made to spectrally adjust the data. These products consist of spatially complete (there are no missing data) land surface albedo data generated at 1-min resolution on an equal-angle grid (0.017^{o}) over 16-day periods. The white-sky albedo products, where white-sky albedo (or bihemispherical reflectance) is defined as the albedo in the absence of a direct component when the diffuse component is isotropic, were selected since the current solar RTM does not support bidirectional surface effects. However, there are plans to eventually use the MOD43B1 BRDF/Albedo Model Parameters Product (16-day, 1 km resolution) to account for bidirectional effects, including the dependence of the surface albedo on solar zenith angle. More details regarding how this database is used are given in Section 3.2.2. When using these products for solar radiance calculations, a Lambertian surface was assumed.

In the IR over land, a monthly mean land surface IR emissivity global product derived by Seeman et al. (2008) was used (http://cimss.ssec.wisc.edu/iremis.) These products are available on a 0.05^{o} grid and are derived from a combination of high spectral resolution laboratory measurements of selected materials and MODIS observed land surface emissivities at six wavenumbers ranging from 699.3 to 2702.7 cm^{-1}. More information on these products is available in Section 3.2.2. When these products are used in IR radiance calculations, a specular surface was assumed. There are plans, however, to incorporate a Lambertian surface into the IR RTM.

Over water surfaces, the model of Sayers (2007), which has been applied to aerosol retrievals, was used for ABI solar bands 1-6. The model separates the surface reflectance into three components: contribution from white caps, contribution from sun glint, and an "underlight" term from radiance emitted just below the water's surface. In the IR, the IRSSEM in CRTM is used to compute the sea surface emissivity for the ABI IR bands (7-16). During the daytime, sea surface albedo for ABI band 7 is assumed as 1-ε, where ε is the IR surface emissivity.

The last piece of the fast solar/IR forward RTM is the method used for computing monochromatic TOA radiances. The SOI RTM (Heidinger et al. 2006) was selected for this purpose for all ABI bands. However, in order to compute solar radiances the model originally developed by Heidinger et al. was modified to include the solar source terms and a Fourier expansion to describe the azimuthal dependence of the radiance field. Our experience has shown the SOI RTM is very fast in comparison to other methods and also has good accuracy.

But before the RTM calculations can be performed, the gas absorption and hydrometeor single-scattering properties must be prepared for input into the SOI RTM. Because the RTM requires optical depth as an extinction parameter in each layer, the hydrometer single-scattering properties must be converted to optical depth for each species. At 0.65 µm, the optical depths for ice hydrometeors (Heymsfield et al. 2003) and liquid hydrometeors are assumed as

$$\tau_{0.65\mu m} = 0.065 IWP^{0.84}$$

and

$$\tau_{0.65\mu m} = \frac{3LWP}{D_e},$$

respectively, where IWP is the ice water path (g/m^2), LWP is the liquid water path (g/m^2), and D_e is the droplet effective diameter (μm). Optical depths at other bands are obtained by scaling the optical depth at 0.65 μm by a ratio of extinction efficiencies:

$$\tau = \frac{Q_{ext}}{Q_{ext,0.65\mu m}} \tau_{0.65\mu m}$$

where Q_{ext} is the extinction efficiency for a given band and $Q_{ext,0.65\ \mu m}$ is the extinction efficiency at 0.65 μm, which is assumed to be 2. This relationship is applied to both solar and IR bands. For the IR bands (8-16) the total optical depth for a layer is defined as the sum of the optical depths due to all hydrometeors plus the optical depth due to gases. However, for the solar bands the total optical depth was computed slightly differently. Because precipitation-sized hydrometeors (rain, and snow and graupel greater than 400 μm in effective diameter) contribute little to the solar radiation emerging at the TOA, the optical depths for these particles were excluded. In addition, solar bands 1-3 also included the optical depth due to Rayleigh scattering, which was obtained from Bodhaine et al. (1991).

The two remaining single-scattering properties needed by the SOI RTM, i.e., single-scatter albedo and the phase function, are a weighted combination of the properties from all the constituents in the atmospheric layer, i.e., gases and hydrometeors. The effective single-scattering albedo (ω_{eff}) representing the combination of all constituents is assumed to be

$$\omega_{eff} = \frac{\sum \omega_i \tau_i}{\tau_{tot}}$$

where ω_i and τ_i are the single-scatter albedo and optical depth of the ith constituent, respectively, and τ_{tot} is the total optical depth. For the Rayleigh optical depth, $\omega = 1$. The expansion coefficients for the phase functions of the different constituents are weighted in a similar way:

$$\chi_\ell = \frac{\sum \chi_{\ell_i} \omega_i \tau_i}{\sum \omega_i \tau_i}$$

where χ_{ℓ_i} is the expansion coefficient of order ℓ for the ith constituent. Gases have no contribution to the phase function since $\omega = 0$.

Different angular resolution was used in the SOI RTM depending on the application. All solar band (1-7) calculations were run with 8 streams, which was found to be a good compromise between accuracy and speed for most situations. In the IR, the appropriate number of streams was determined automatically depending on the degree of scattering. The degree of scattering can be defined as the product, $\omega\tau$, integrated through the entire atmosphere, which is sometimes called the scattering optical depth. If $(\omega\tau)_{\mathrm{tot}} \leq 0.01$, two streams were used, otherwise four streams were used. All calculations used the delta transformation (Joseph et al. 1976) to greatly improve the solution's accuracy for strongly forward peaked phase functions.

Table 1. ABI band characteristics (adapted from Schmit et al. 2005).

Band No.	Wavelength range (μm)	Wavenumber range (cm^{-1})	Sample use
1	0.45-0.49	-	Daytime aerosol over land, coastal water mapping
2	0.59-0.69	-	Daytime clouds, fog, insolation, winds
3	0.846-0.885	-	Daytime vegetation/burn scar, aerosol over water, winds
4	1.371-1.386	-	Daytime cirrus
5	1.58-1.64	-	Daytime cloud phase and particle size, snow
6	2.225-2.275	-	Daytime land/cloud properties, particle size, vegetation, snow
7	3.80-4.00	2500.0-2631.6	Surface, cloud, fog at night, fire, winds
8	5.77-6.6	1515.15-1733.1	High-level water vapor, winds
9	6.75-7.15	1398.6-1481.5	Mid-level water vapor, winds
10	7.24-7.44	1344.09-1381.2	Low-level water vapor and SO_2
11	8.3-8.7	1149.4-1204.8	Stability, cloud phase, dust, SO_2, rainfall
12	9.42-9.8	1020.4-1061.6	Ozone, turbulence, winds
13	10.1-10.6	943.40-990.10	Surface and clouds
14	10.8-11.6	862.07-925.93	Imagery, SST, clouds, rainfall
15	11.8-12.8	781.25-847.46	Total water, ash, SST
16	13.0-13.6	735.29-769.23	Air temperature, cloud heights and amounts

Table 2. Characteristics of proxy ABI surface albedo datasets derived from MODIS data.

ABI band	Central Wavelength (μm)	MODIS band	Central Wavelength (μm)
1	0.47	3	0.47
2	0.64	1	0.659
3	0.865	2	0.858
4	1.378	5	1.24
5	1.61	6	1.64
6	2.25	7	2.13

2.4 *Model Development History*

Initial release of the fast IR RTM occurred in August 2007. Only relatively minor changes have been made to the code, including a bug discovered in the SOI RTM that affected the calculation of ABI band 7 radiances (September ’07) and the addition of an option to compute weighting functions (October ‘07).

The fast solar RTM was initially released in October 2007. Important bug fixes and improvements in the forward model system include:

- Fixed zenith angle initialization for the SOI RTM (Nov 2007)
- Replaced routine that computed relative solar azimuth angle (Nov 2007)
- Increased maximum number of interactions in the SOI RTM (Dec 2007)
- Added Rayleigh scatter and the Sayer (2007) sea surface reflectance model (Dec 2007)
- Added gas transmittance tables and scattering property tables for SEVIRI and the GOES-12 imager; added option for other instruments to RTM input (Feb 2008)

3 Fast Model Implementation

3.1 *Code and Data Access*

Code and input data for the solar/IR RTM are available upon request.

3.2 *Data File Description*

3.2.1 Input Data

The primary input data used for the fast solar/IR RTM is 3D NWP model data output from the WRF model. The data files are provided in netCDF. The major difference between our earlier datasets (e.g., described in *Fulldisk Atmospheric Profile Dataset Description and Documentation*) is that the model variables are retained at the native model levels and are not interpolated to the 101 standard pressure levels. However, climatic profiles of temperature, water vapor mixing ratios, and ozone concentrations are still needed above the WRF model top, which are based on some of the 101 standard levels. The 3D prognostic fields used as input to the RTM include pressure, temperature, water vapor mixing ratio, and mixing ratios for five hydrometeor types. Also used are 3D diagnosed fields of the effective diameter for the five hydrometeor types and 2D prognostic fields of 10 m height wind and surface skin temperature.

Coefficient files needed by Compact-OPTRAN for the IR RTM are available in a tarball included with all CRTM releases. These files are binary and direct access. Two sets of files are required. Files with *SpcCoeff* included in their name contain spectral information such as the central wavenumber for the bands, the Planck function coefficients, and the polychromatic factors used to adjust the equivalent blackbody temperature. Files with *TauCoeff* in their name contain the polynomial coefficients used in reconstructing the transmittances. Table 3 includes filenames for many of the files used to simulate various instruments in our research.

Table 3. Coefficient files used for Compact-OPTRAN.

Filename	Satellite	Instrument	Description
abi_gr.SpcCoeff.bin	GOES-R	ABI	Spectral coefficients
abi_gr.TauCoeff.bin	GOES-R	ABI	Transmittance coefficients
modis_terra.SpcCoeff.bin	Terra	MODIS	Spectral coefficients
modis_terra.TauCoeff.bin	Terra	MODIS	Transmittance coefficients
modis_aqua.SpcCoeff.bin	Aqua	MODIS	Spectral coefficients
modis_aqua.TauCoeff.bin	Aqua	MODIS	Transmittance coefficients
airs_aqua.SpcCoeff.bin	Aqua	AIRS	Spectral coefficients
airs_aqua.TauCoeff.bin	Aqua	AIRS	Transmittance coefficients
seviri_msg01.SpcCoeff.bin	MSG-1	SEVIRI	Spectral coefficients
seviri_msg01.TauCoeff.bin	MSG-1	SEVIRI	Transmittance coefficients
imgr_g08.SpcCoeff.bin	GOES-8	Imager	Spectral coefficients
imgr_g08.TauCoeff.bin	GOES-8	Imager	Transmittance coefficients
imgr_g09.SpcCoeff.bin	GOES-9	Imager	Spectral coefficients
imgr_g09.TauCoeff.bin	GOES-9	Imager	Transmittance coefficients
imgr_g10.SpcCoeff.bin	GOES-10	Imager	Spectral coefficients
imgr_g10.TauCoeff.bin	GOES-10	Imager	Transmittance coefficients
imgr_g11.SpcCoeff.bin	GOES-11	Imager	Spectral coefficients
imgr_g11.TauCoeff.bin	GOES-11	Imager	Transmittance coefficients
imgr_g12.SpcCoeff.bin	GOES-12	Imager	Spectral coefficients
imgr_g12.TauCoeff.bin	GOES-12	Imager	Transmittance coefficients
imgr_g13.SpcCoeff.bin	GOES-13	Imager	Spectral coefficients
imgr_g13.TauCoeff.bin	GOES-13	Imager	Transmittance coefficients

3.2.2 Ancillary Data

The only required ancillary data sets are the surface radiative property databases. The global IR land surface emissivity databases are stored as binary files with direct access. Each record contains a single latitude/longitude point along with slope and intercept data (7 points each) for computing surface emissivity between 8 spectral inflection points (699.3007, 925.9259, 1075.269, 1204.819,1315.790, 2000.000, 2325.581, 2702.703 cm^{-1}). The file record length is 64 bytes. To obtain the surface emissivity value for a given WRF model gridpoint the database is interpolated both spectrally and spatially.

The second ancillary data sets are the surface albedo (white sky) products. The albedo products were first converted from HDF into flat binary files. These binary files were then reorganized as direct access binary files. Each record consists of scaled two byte integers for 21,600 longitude bins, giving a record length of 43,200 bytes. There are 10,800 records in a file, each representing a latitude bin. Separate files (also binary and direct access) are provided for the latitude and longitude grid values. To obtain the surface albedo for a given WRF model gridpoint the albedo database is linearly interpolated.

3.2.3 Look-up Tables

Numerous look-up tables are needed by the solar/IR RTM. First is the single-scattering properties tables. For the solar bands, the extinction efficiency and single-scatter albedo are stored as separate ASCII files for each of the instruments and hydrometeor phases (ice or liquid). These properties are given at discrete effective diameters. For liquid hydrometeors, they occur at 2, 4, 6, 8, 10, 12, 16, 20, 25, 37, 50, 75, 100, 125, 150, and 175 μm; for ice hydrometeors they range from 10 to 180 μm at 10 μm increments. In the lookup tables themselves, the data are organized as follows: First column is instrument band number, second is hydrometeor effective diameter, third is extinction efficiency, and fourth is single-scatter albedo. The third single-scattering property, the phase function, is represented as Legendre polynomial expansion coefficients in binary, direct access files for each of the instruments and hydrometeor phases (see Table 4.) Coefficients are provided at the same effective diameter values as the other properties. Each record includes the instrument band number, the effective diameter value, followed by 3000 coefficients. In practice, only the first 64 coefficients are read into the table.

For the IR single-scattering properties, the lookup tables are similar but have higher spectral resolution and are not provided for individual instrument bands. The extinction efficiency and single-scatter albedo tables for ice hydrometeors have the same effective diameters as for the solar bands but range instead from 100 to 3250 cm^{-1} with 1 cm^{-1} increments. However, the tables for the liquid hydrometeor properties are somewhat different. They are provided with effective radii that range from 1 to 550 μm with 32 discrete points and for wavenumbers ranging from 100 to 3246.7532 cm^{-1} with only 49 discrete points. These tables differ from the other tables because they were obtained from Dave Turner based on Lorenz-Mie calculations performed by Ping Yang. The phase function expansion coefficient tables, on the other hand, are generally organized the same as the solar bands but instead each hydrometeor diameter has its own file, which was done to reduce file size. Also, the contents of each record is slightly different than the solar band tables in that the wavenumber value is included, as well as the number of significant terms in the series (based on an arbitrary threshold), which is followed by the 3000 coefficients. Table 5 provides more information concerning these lookup tables.

Table 4. Single-scattering property lookup tables used for the solar bands.

Filename	No. bands	Record length (bytes)	Description
ABI_bands01-07_iceprop.txt	7	-	Ice hydrometeor single-scattering properties (extinction efficiency, single-scatter albedo, asymmetry factor) for the ABI
ABI_bands01-07_Mieprop.txt	7	-	Liquid hydrometeor single-scattering properties for the ABI
IMGRG12_bands01-02_iceprop.txt	2	-	Ice hydrometeor single-scattering properties for the GOES-12 Imager
IMGRG12_bands01-02_Mieprop.txt	2	-	Liquid hydrometeor single-scattering properties for the GOES-12 Imager
SEVIRI_bands01-04_iceprop.txt	4	-	Ice hydrometeor single-scattering properties for the SEVIRI
SEVIRI_bands01-04_Mieprop.txt	4	-	Ice hydrometeor single-scattering properties for the SEVIRI
PFexpcoefice_ABI_bands01-07.bin	7	12016	Ice hydrometeor phase function expansion coefficients for the ABI
PFexpcoefMie_ABI_bands01-07.bin	7	12016	Liquid hydrometeor phase function expansion coefficients for the ABI
PFexpcoefice_IMGRG12_bands01-02.bin	2	12016	Ice hydrometeor phase function expansion coefficients for the GOES-12 Imager
PFexpcoefMie_IMGRG12_bands01-02.bin	2	12016	Liquid hydrometeor phase function expansion coefficients for the GOES-12 Imager
PFexpcoefice_SEVIRI_bands01-04.bin	4	12016	Ice hydrometeor phase function expansion coefficients for the SEVIRI
PFexpcoefMie_SEVIRI_bands01-04.bin	4	12016	Liquid hydrometeor phase function expansion coefficients for the SEVIRI

Table 5. Single-scattering property lookup tables used for the IR bands (ν is wavenumber.)

Filename	No. Bands	Record size (bytes)	Description
IR_mix1_ssalb.dat	3150	-	Single-scatter albedo for ice hydrometeors as a function of D_e and ν
IR_mix1_qext.dat	3150	-	Extinction efficiency for ice hydrometeors as a function of D_e and ν
IR_mix1_asy.dat	3150	-	Asymmetry factor for ice hydrometeors as a function of D_e and ν
ssp_db.Watersphere	49	-	Liquid hydrometeor properties
PFexpcoefice_100-3250_10microns.dat	3150	12016	Ice hydrometeor phase function expansion coefficients from 100 to 3250 cm^{-1} at D_e = 10 μm
PFexpcoefice_100-3250_20microns.dat	3150	12016	Same as above but D_e = 20 μm
PFexpcoefice_100-3250_30microns.dat	3150	12016	Same as above but D_e = 30 μm
PFexpcoefice_100-3250_40microns.dat	3150	12016	Same as above but D_e = 40 μm
PFexpcoefice_100-3250_50microns.dat	3150	12016	Same as above but D_e = 50 μm
PFexpcoefice_100-3250_60microns.dat	3150	12016	Same as above but D_e = 60 μm
PFexpcoefice_100-3250_70microns.dat	3150	12016	Same as above but D_e = 70 μm
PFexpcoefice_100-3250_80microns.dat	3150	12016	Same as above but D_e = 80 μm
PFexpcoefice_100-3250_90microns.dat	3150	12016	Same as above but D_e = 90 μm
PFexpcoefice_100-3250_100microns.dat	3150	12016	Same as above but D_e = 100 μm
PFexpcoefice_100-3250_110microns.dat	3150	12016	Same as above but D_e = 110 μm
PFexpcoefice_100-3250_120microns.dat	3150	12016	Same as above but D_e = 120 μm
PFexpcoefice_100-3250_130microns.dat	3150	12016	Same as above but D_e = 130 μm
PFexpcoefice_100-3250_140microns.dat	3150	12016	Same as above but D_e = 140 μm
PFexpcoefice_100-3250_150microns.dat	3150	12016	Same as above but D_e = 150 μm
PFexpcoefice_100-3250_160microns.dat	3150	12016	Same as above but D_e = 160 μm
PFexpcoefice_100-3250_170microns.dat	3150	12016	Same as above but D_e = 170 μm
PFexpcoefice_100-3250_180microns.dat	3150	12016	Same as above but D_e = 180 μm
PFexpcoefMie_100-3250_2microns.dat	3150	12016	Liquid hydrometeor phase function expansion coefficients from 100 to 3250 cm^{-1} for D_e = 2 μm
PFexpcoefMie_100-3250_4microns.dat	3150	12016	Same as above but D_e = 4 μm
PFexpcoefMie_100-3250_6microns.dat	3150	12016	Same as above but D_e = 6 μm
PFexpcoefMie_100-3250_8microns.dat	3150	12016	Same as above but D_e = 8 μm
PFexpcoefMie_100-3250_10microns.dat	3150	12016	Same as above but D_e = 10 μm
PFexpcoefMie_100-3250_12microns.dat	3150	12016	Same as above but D_e = 12 μm
PFexpcoefMie_100-3250_16microns.dat	3150	12016	Same as above but D_e = 16 μm
PFexpcoefMie_100-3250_20microns.dat	3150	12016	Same as above but D_e = 20 μm
PFexpcoefMie_100-3250_25microns.dat	3150	12016	Same as above but D_e = 25 μm
PFexpcoefMie_100-3250_37microns.dat	3150	12016	Same as above but D_e = 37 μm
PFexpcoefMie_100-3250_50microns.dat	3150	12016	Same as above but D_e = 50 μm
PFexpcoefMie_100-3250_75microns.dat	3150	12016	Same as above but D_e = 75 μm
PFexpcoefMie_100-3250_100microns.dat	3150	12016	Same as above but D_e = 100 μm
PFexpcoefMie_100-3250_125microns.dat	3150	12016	Same as above but D_e = 125 μm
PFexpcoefMie_100-3250_150microns.dat	3150	12016	Same as above but D_e = 150 μm
PFexpcoefMie_100-3250_175microns.dat	3150	12016	Same as above but D_e = 175 μm

Another set of lookup tables is needed by the gas transmittance model for the solar bands. Each file represents a separate band and is binary and direct access. Each record in the file has a length of 192 bytes containing 48 atmospheric transmittances over a wide range of values. These transmittances are provided for each of seven gas species, 72 pressure values, and seven temperature values. To obtain a transmittance for a given gas species, pressure and temperature, polynomial interpolation of the lookup tables is used. Table 6 summarizes these files.

The final lookup table is used by the IRSSEM and comes with official releases of the CRTM. The filename is *EmisCoeff.bin*. The table consists of sea surface emissivity for near surface wind speeds from 0 to 15 m/s, zenith angles from 0 to 65^o and spectral wavenumbers from 600 to 3000 cm^{-1}.

Table 6.Band model lookup tables used for the solar bands.

Filename	Description
ch01tb.bi	ABI band 1
ch02tb.bi	ABI band 2
ch03tb.bi	ABI band 3
ch04tb.bi	ABI band 4
ch05tb.bi	ABI band 5
ch06tb.bi	ABI band 6
ch07tb.bi	ABI band 7
ch01tb_imgrg12.bi	GOES-12 imager band 1
ch02tb_imgrg12.bi	GOES-12 imager band 2
ch01tb_sevmsg01.bi	SEVIRI band 1
ch02tb_sevmsg01.bi	SEVIRI band 2
ch03tb_sevmsg01.bi	SEVIRI band 3
ch04tb_sevmsg01.bi	SEVIRI band 4

3.2.4 Outputs

One netCDF file is created from either the solar RTM or the IR RTM. The file contains 2D fields of either simulated solar radiances/reflectances or IR radiances/brightness temperatures, as well as other information of interest, at each grid point of the input WRF model domain (see Tables 7 and 8 for more details.) Although users can specify the name of the output file themselves, the filename convention used here was

TOA_*III_yyyy_mmdd_tttt_cc_rr*.cdf

where *III* is the instrument name (e.g., ABI, SEV, G12), *yyyy* is year, *dd* is day of the month, *mm* is month of the year, *tttt* is universal time in UTC, and *cc* and *rr* are the column and row indices for an individual “data cube.” Although not described here, these individual data cube files are then sewn together to form one large file that covers the entire WRF domain. The final step remaps the reflectance and/or radiance data to the projection of the desired instrument.

Table 7. Variables contained in the output file of the solar forward RTM.

Variable name	Description	Units
Altitude	Height of terrain	Meters
LANDCLAS	WRF model land class index	None
Lat	WRF model latitude	Degrees north
Lon	WRF model longitude	Degrees east
CLD_INDT	Cloud indicator (0: clear; 1: ice; 2: liquid; 3: mixed)	None
obszen	Local zenith angle	Degrees
solarzen	Solar zenith angle	Degrees
azimuth	Relative solar azimuth angle	Degrees
landflag	Land flag or mask	None
visopt_depth	Cloud visible optical depth	None
III_rad_b##	Radiance for band ## of instrument III (e.g., ABI)	mW/(m^2steradian cm^{-1})
III_refl_b##	Reflectance for band ## of instrument III	None
III_salb_b##	Surface albedo for band ## of instrument III	None

Table 8. Variables contained in the output file of the IR forward RTM.

Variable name	Description	Units
Lat	WRF model latitude	Degrees north
Lon	WRF model longitude	Degrees east
Altitude	Height of terrain	Meters
landmask	Land mask	None
CLD_INDT	Cloud indicator (0: clear; 1: ice; 2: liquid; 3: mixed)	None
visopt_depth	Cloud visible optical depth	None
zenang	Local zenith angle	Degrees
tskin	WRF model surface skin temperature	Kelvin
sfcEmis_b##	Surface emissivity for band ##	None
III_rad_b##	Radiance for band ## of instrument III (e.g., ABI)	mW/(m^2steradian cm^{-1})
III_tb_b##	Brightness temperature for band ## of instrument III	Kelvin

3.3 *Code Features and Requirements*

The solar RTM and the IR RTM are two separate programs. The main program for the solar RTM code is contained in *solfrtm.f90*, while the main program for the IR RTM is contained in *irfrtm.f90*. Other important routines are described in Tables 9 and 10.

Nearly all testing of the RTM code was done in a Linux environment on a 64-bit Opteron cluster. While previous forward model code was tested for several different compilers, testing for the solar/IR RTM code was done only with the Intel F90 (v9.1) compiler. A script to build the executable for the Intel F90 compiler is provided in *build_ifort.* The IR RTM code must be linked with the CRTM library, which has the name libCRTM.a (we used Version 1.1, release 704). Both sets of code also require the netCDF libraries be installed on the user's system. Version 3.6.1 of the netCDF libraries was used in our tests.

Memory requirements for the RTM codes will depend entirely on the size of the input NWP model data set to be processed. For a 3D WRF model grid with 256 x 256 horizontal grid points and about 50 vertical levels, the amount of resident memory needed can be expected to be several hundred MB.

Table 9. Brief description of selected routines and modules in the IR RTM code.

File name	Routine or module name	Description
irfrtm.f90	irfrtm	Main driver for the IR RTM. Loads all necessary input data sets (WRF model data, lookup tables, CRTM data, surface emissivity), computes TOA radiances and outputs data into a netCDF file.
forward_rtm.f90	forward_rtm	Prepares profile data, assigns cloud properties and surface properties, computes TOA radiances for each grid point in the NWP model domain.
SOI_rt_model2.f90	soi_rt	RTM solver that computes a monochromatic radiance at the TOA assuming only thermal sources.
ncdf_util.f90	open_ncdf close_ncdf read_WRF_ncdf write_outrad_ncdf	Utilities to read and create netcdf files. Also contains main data structures.
get_visopd.f90	get_visopd	Computes visible optical depths for hydrometeors within each atmospheric layer.
profile_util.f90	hypsometric lev_to_lay prep_fwdmodel_profs	Utilities to process profile data and to add level data above the NWP model top.
scattering_prop.f90	get_cloud_opt_prop ice_scat_tables liq_phasef_tables ice_phasef_tables	Routines to load single-scattering lookup tables and for interpolating the tables.
geometry.f90	observation_zenith_angle sat_instrument_geometry	Computes and assigns geometric quantities, such as local zenith angle.
sfc_emiss.f90	GetEmissLand getEmissSlopeInt	Routines to load and interpolate surface emissivity database.
open_file_format.f90	open_file_format	Assigns format type for binary input files according to compiler
Type_Kinds.f90	Type_Kinds	Holds specification kinds for variable declaration.

Table 10. Brief description of selected routines and modules in the solar RTM code.

File name	Routine or module name	Description
solfrtm.f90	solrtm	Main driver for the IR RTM. Loads all necessary input data sets (WRF model data, lookup tables, CRTM data, surface emissivity), prepares profile data, assigns cloud properties and surface properties, computes TOA radiances/reflectances for each grid point in the NWP model domain, and outputs data into a netCDF file.
soi_rt_model_az_10-10-07.f90	soi_solar_rt	RTM solver (version October 10, 2007) that computes a monochromatic azimuthal radiance field at the TOA assuming only a solar source.
ncdf_util.f90	open_ncdf close_ncdf read_WRF_ncdf write_outrad_ncdf	Utilities to read and create netcdf files. Also contains main data structures.
get_visopd.f90	get_visopd	Computes visible optical depths for hydrometeors within each atmospheric layer.
Irtran.f	irtran	Computes layer atmospheric transmittances due to gases.
profile_util.f90	hypsometric lev_to_lay prep_fwdmodel_profs	Utilities to process profile data and to add level data above the NWP model top.
scattering_prop_solar.f90	liq_scat_tables ice_scat_tables liq_phasef_tables ice_phasef_tables	Routines to load single-scattering lookup tables and for interpolating the tables.
geometry.f90	observation_zenith_angle sat_instrument_geometry	Computes and assigns geometric quantities, such as local zenith angle.
surface_reflectance.f90	ssrm getAlbedoLand	Routines that load and interpolate land surface albedo data and compute sea surface reflectance.
open_file_format.f90	open_file_format	Assigns format type for binary input files according to compiler
Type_Kinds.f90	Type_Kinds	Holds specification kinds for variable declaration.

3.4 *Example*

A specific example is provided for building executables for the RTM codes and running the executables using input list files. These files are in ASCII format and supply input/output filenames and option settings to the program through standard input.

On a Linux system, for example, the code can be compiled using the Intel F90 compiler and executed by typing the following at the command line:

```
./build_ifort
./irfm.e < input_IR.lis
```

or

```
./solfm.e < input_solar.lis
```

The contents of a typical input file might look like this for simulating the ABI thermal IR bands:

```
abi_gr       ! Instrument OPTIONS: e.g., abi_gr, airs_aqua, seviri_msg01
/home/tomg/goesr/CRTM/REL-1.1_alpha.rev704.2007-06-25.JCSDA_CRTM/coeffs/
/home/tomg/goesr/CRTM/REL-1.1_alpha.rev704.2007-06-25.JCSDA_CRTM/coeffs/
/home/tomg/gfm/data/ssp_db.Watersphere
/home/tomg/gfm/data/IR_mix1_*
/home/tomg/gfm/data/PFexpcoefMie_100-3250_*
/home/tomg/gfm/data/PFexpcoefice_100-3250_*
/home/tomg/goesr/CRTM/REL-1.1_alpha.rev704.2007-06-
25.JCSDA_CRTM/coeffs/EmisCoeff.bin
/home/tomg/gfm/data/0324_2005_new_seif_eta_1410utc_2_3.nc
/scratch/tomg/global_emis_mar.bin
GEO          ! Satellite type - GEO or LEO. For GEO supply satellite subpoint
             longitude on next line; for LEO supply filename and full path for
             netcdf file
-75.
SOI          ! Set number of SOI streams (Use "SOI" for most efficient &
             accurate calcs; otherwise, use 2,4,6,8,...)
NORMAL       ! Mode of radiance calculations: NORMAL is for all-sky radiances
             and CLEAR is for clear sky only
T            ! Verbose output, T for TRUE and F for FALSE
/home/tomg/gfm/data/ABIIRtest.nc
```

and this for the ABI solar bands:

```
abi_gr           ! Instrument options: abi_gr, imgr_g12, seviri_msg01
/home/tomg/gfm/data/
/home/tomg/gfm/data/
/home/tomg/gfm/data/EmisCoeff.bin
/scratch/tomg/ncsa_msg_3000m_0816_2006.0000utc_14_18.nc
ALL     ! Number of channels to process and selected channels (e.g. 3-123).
        To select all channels, type ALL
/home/tomg/gfm/data/AlbMap.Latitude.bin
/home/tomg/gfm/data/AlbMap.Longitude.bin
/scratch/tomg/AlbMap.2003.161.0.47.bin
/scratch/tomg/AlbMap.2003.161.0.659.bin
```

```
/scratch/tomg/AlbMap.2003.161.0.858.bin
/scratch/tomg/AlbMap.2003.161.1.24.bin
/scratch/tomg/AlbMap.2003.161.1.64.bin
/scratch/tomg/AlbMap.2003.161.2.13.bin
/scratch/tomg/global_emis_slopeInterc_MYD11C3.A2003152_wvnum.bin.le
-75.
8       ! Number of streams
0.0     ! SOI convergence criterion. To use default (2.e-5), set to 0
F       ! Truncate doubling? T or F
0.0     ! Tolerance for Fourier expansion of azimuthal radiance field. To use
        default (2.e-4), set to 0
F       ! Use adding instead of SOI? T or F
Y       ! Verbose output: Y or N
ABIsolartest.nc
```

Several input options that are available for the solar SOI RTM are described as follows. The SOI convergence criterion is the criterion used to stop the SOI iterations. It is based on a comparison between radiances computed for a given SOI iteration and radiances computed from the previous iteration. A switch for truncated doubling is included that allows for a truncation of the series expansion of the 1-*RR* term (where *R* is the reflection matrix), which the SOI RTM uses to speed up doubling calculations. A tolerance for the Fourier expansion of the azimuthal radiance field is made available in order to provide flexibility in truncating the Fourier series. Another option allows the SOI algorithm for computing radiances at atmospheric levels to be replaced by the adding algorithm by setting this option to TRUE. A traditional adding/doubling model, therefore, can be implemented by simply setting the truncated doubling option to FALSE and the adding algorithm option to TRUE.

A useful option available for the IR RTM is the ability to compute TOA radiances for an instrument in LEO. However, this requires an input file that supplies the local zenith angle information for the instrument. The only requirements for the file is that it is in netCDF and at a minimum has the following attributes and variables:

- Global attribute called “OUTPUT_TIME” that corresponds to the time of the satellite overpass and which has the same format as the input WRF model data file.
- Dimensions for the size of the satellite swath are called “acrosstrack” (the number of samples or pixels in a scan line) and “alongtrack” (the number of scan lines).
- Three variable grids named “Lat”, “Lon”, and “szen” (contains local zenith angle).

See routine *read_LEOdat_ncdf* in module *ncdf_util* for additional information. In the example above for the IR RTM input file, changing the satellite type and specifying an input file and its full path is needed to simulate radiances for an instrument in LEO:

```
LEO          ! Satellite type - GEO or LEO. For GEO supply satellite subpoint
             longitude on next line; for LEO supply filename and full path for
             netcdf file
/home/tomg/gfm/data/MYD06_2005083_1405-1420.nc
```

4 References

Baum, B. A., A. J. Heymsfield, P. Yang, and S. T. Bedka, 2005a: Bulk scattering properties for the remote sensing of clouds. Part I: Microphysical data and models. J. Appl. Meteor., 44, 1885-1895.

Baum, B. A., P. Yang, A. J. Heymsfield, S. Platnick, M. D. King, Y.-X. Hu, and S. T. Bedka, 2005b: Bulk scattering properties for the remote sensing of clouds. Part II: Narrowband models. J. Appl. Meteor., 44, 1896-1911.

Bodhaine, B. A., N. B. Wood, E. G. Dutton, and J. R. Slusser, 1999: On Rayleigh optical depth calculations. J. Atmos. Ocean Technol., 16, 1854-1861.

Heidinger, A. K., C. O'Dell, R. Bennartz, and T. Greenwald, 2006: The successive-order-of-interaction radiative transfer model. Part I: Model development. J. Appl. Meteor. and Clim., 45, 1388-1402.

Heymsfield, A. J., S. Matrosov, and B. Baum, 2003: Ice water path-optical depth relationships for cirrus and deep stratiform ice cloud layers. J.. Appl. Meteor., 42, 1369-1390.

Joseph, J. H., W. J. Wiscombe, and J. A. Weinman, 1976: The delta-Eddington approximation for radiative flux transfer. J. Atmos. Sci., 33, 2452-2459.

McMillin L. M., L. J. Crone, M. D. Goldberg, and T. J. Kleespies, 1995: Atmospheric transmittance of an absorbing gas, 4. OPTRAN: A computationally fast and accurate transmittance model for absorbing gases with fixed and variable mixing ratios at variable viewing angles. Appl. Opt., 34, 6269–6274.

Sayer, A., 2007: A sea surface reflectance model suitable for use with AATSR aerosol retrieval. University of Oxford, AOPP Memorandum 2007.2.

Schmit, T. J., M. M. Gunshor, W. P. Menzel, J. J. Gurka, J. Li, and A. S. Bachmeier, 2005: Introducing the next-generation advanced baseline imager on GOES-R. Bull. Amer. Meteor. Soc., 1079-1096.

Seeman, S. W., E. E. Borbas, R. O. Knuteson, G. R. Stephenson, and H.-L. Huang, 2008: Development of a global infrared land surface emissivity database for application to clear sky sounding retrievals from multispectral satellite radiance measurements. J. Appl. Meteor. and Clim., 47, 108-123.