1. Introduction
This document describes the methodology used to generate simulated satellite imagery from modeled atmospheric and surface representations. The objective is to realistically mimic the characteristics of real-world imagery by accurately modeling the at-the-sensor radiance levels resulting from the application of a physics-based radiative transfer model to the underlying environmental conditions as reflected by the model representation. This is in contrast to other techniques of generating NWP model-based simulated satellite imagery that instead rely on simple empirical schemes to translate model-derived cloud layers into radiance values.

The important advantages to the AER-developed framework discussed here include:
- The final radiance scene is the result of the application of first principles radiative transfer modeling through a 3D atmospheric volume allowing for solar and viewing angles to be directly addressed and realistic spectral signatures to be achieved
- The assignment of radiative properties to model volumes is precisely applied for each type of atmospheric phenomena and easily modified to balance fidelity/accuracy vs computational efficiency
- Modifications to the process to improve overall image quality are achieved through independent schemes to address each issue rather than bulk adjustments to a color or transparency table

Work on this framework to date has focused on the use of environment representations provided by the Environmental Scenario Generator (ESG) which are typically either MASS or WRF model based. However, the techniques developed here are not model specific and could routinely be applied to alternate model representations, such as the GFS or COAMPS.

The satellite imagery generation process is divided into two main elements: (1) physical modeling of the top-of-atmosphere radiation for a wavelength specific sensor at a realistic viewing orientation and (2) image processing and production of files in standard image file formats (e.g., PNG, NITF, KML). Since the physical modeling portion consumes about 95% of the total processing time, the processing is broken into two distinct executable applications allowing for the production of alternative image types (e.g. providing for different color schemes, formats, image labeling) without the need to rerun the radiative transfer code. An overview of the processing steps is provided in Figure 1.

![Image generation processing flow diagram]

Figure 1: Image generation processing flow.
2. Physical modeling

The physical modeling application, termed RADSIM for radiation simulation, computes at-the-sensor radiances on a model grid point basis from the quantitative depiction of the natural environment. Infrared and visible band radiances observed by a satellite sensor are a function of its viewing angle on the scene and influenced by a combination of the underlying surface radiance and the atmospheric attenuation from water vapor in clear-air, cloud water and ice droplets, and precipitation. RADSIM takes a first-principles approach to radiation simulation that analyzes the radiative properties of the model atmosphere and then executes radiative transfer calculations solving for satellite-observed radiances.

The radiative transfer calculations employ an AER-developed model called CHARTS: Code for High-Resolution Accelerated Radiative Transfer with Scattering (Moncet and Clough, 1997). The CHARTS OSS-SCAT (Optimal Spectral Sampling with Scattering) module implements a fast adding-doubling method that utilizes atmospheric scattering and absorption optical thicknesses generated by the Line-By-Line Radiative Transfer Model (LBLRTM; Clough et al., 2005). Up- and down-welling atmospheric radiative transfer calculations can be performed on optically thin sublayers, allowing the more efficient single-scattering approximation to be invoked without loss of model accuracy. The adding-doubling approach uses matrices that quantify the coupling between incident, scattered, absorbed, and transmitted radiances at a pre-defined number of ingoing/outgoing directions at the layer boundaries. The higher the number of sublayers and stream directions used in the solution, the more precisely the final radiance field will represent an exact model solution but at the expense of increased computational cost. In the current implementation, RADSIM uses 4 stream directions and retains the vertical resolution of the forecast model atmospheric column representation (e.g., 38 sigma levels from WRF and 14 pressure levels from MASS). At this level of fidelity, a typical IR and Visible satellite image produced from 24 km WRF data takes about 2 minutes to compute on a single processor.

Execution of the OSS-SCAT model requires both cloud and clear-air layer radiative properties that must be calculated from the atmospheric fields available from the forecast model. The RADSIM application acts as a pre-preprocessor for the OSS-SCAT model to develop consistent atmospheric profiles independent of the source atmospheric model. The clear-air characterization of the profile is defined by dew point and liquid water path per layer, both of which are routinely derived from any atmospheric model source. The characterization of the radiative properties for cloudy layers is more complex and does have a dependence on the model source. The two cases supported to date were developed specifically for the content available from the WRF and MASS models, but these approaches can be generalized to “explicit moisture physics” and “basic moisture modeling”, respectively, as most NWP models fall into one of these two categories.

The basic approach relies on an inferred determination of the occurrence of cloud based on profiles of temperature and relative humidity only. This approach is used for the MASS model data from ESG, but would also be applicable for general use with global models for low-resolution satellite imagery. The cloud fraction, $\sigma_c(l)$, is estimated per layer, $l$, as:

$$\sigma_c(l) = \left(\frac{4RH_{i,w}(l)}{100} - 3\right)^3$$

where $RH_{i,w}$ is the model RH adjusted for air temperature (i.e., to RH with respect to ice, water, or a mixture). For layers determined to have clouds (e.g., $\sigma_c > 0.01$), the cloud liquid water (CLW) is set to fixed values for low and mid-level clouds, and estimated from temperature following the method of Liou (1992) for high clouds.

In the case of the WRF model, CLW profiles can be obtained directly from the provided cloud and ice mixing ratio fields. However, the standard WRF output does not adequately reflect
clouds produced by convective processes, and therefore an adjustment to the CLW profiles is made based on the surface convective precipitation, $P_c$ [mm/hr], as:

$$CLW_c = CLW(p,T) \cdot (P_c / 5)^{1/2} \quad (2)$$

where $CLW(p,T)$ is derived using the same equation 1 above. The total CLW for each layer is then taken as the maximum of the original model-based CLW, the precipitation-based $CLW_c$, or the more simplistic $CLW(p,T)$ for cases where $P_c$ is very large (included to reflect clouds on the periphery of precipitating regions).

Although these techniques for analyzing the cloud properties from a model atmosphere are approximate, they represent a systematic approach for the assignment of radiation properties to each layer of the model atmosphere. Improvement to these techniques can be developed in conjunction with improvements to the underlying atmospheric state represented in numerical weather model fields, and will improve the accuracy of the resulting radiances.

Other fields employed from the atmospheric models include surface air and skin temperatures, precipitation fields, total cloud cover, and the model’s land/sea mask.

The remainder of the RADSIM processing is independent of atmosphere model source. Solar zenith angles are computed based on the valid date/time of the model atmosphere. Sensor viewing angles are computed based on the weather satellite location over the equator closest to the central longitude of the model grid. For land points, input satellite-derived surface reflectance is adjusted to the specific sensor band to be simulated and, in the limiting case (wavelength > 5 μm), emissivity is set to 1.0 (equivalent to zero reflectance). For water points, (1) non-directional reflectance is band-tabulated with all values in the 0.0 to 0.01 range and (2) bidirectional solar reflectance (wavelengths < 4 μm) is calculated with the Cox and Munk (1954) model based on the 10 m wind speed and direction from the model. Lastly, cloud-particle effective diameter, absorption and scattering efficiencies, asymmetry parameter, and density are extracted by layer temperature from pre-computed look-up tables.

RADSIM’s full radiative transfer physics model is only applied to window-band simulations due in part to the additional computational expense incurred in bands with higher absorption rates throughout the atmospheric column. For example, the full model is utilized to produce imagery in the thermal infrared (TIR, e.g., 10.8 μm) and visible (VIS, e.g., 0.64 μm) bands. For non-window bands (e.g., the water vapor band at 6.7 μm) we take a hybrid approach that continues to treat cloud layers physically while approximating radiative parameters in non-cloud layers based on pre-calculated standard atmospheric profiles. In this approach, the optical depth profile of the model atmosphere is found by interpolating between the cataloged profiles based on model total precipitable water content. Simulated water vapor band imagery is then produced using a single-stream radiative transfer model applied to the interpolated optical depths and the model temperature and cloud properties profiles. This approach enables faster calculations while producing imagery that realistically captures the water vapor, temperature, and cloud distributions represented in the model atmosphere.

### 3. Image processing

The application IM2FILE produces satellite imagery products in standard file formats based on the RADSIM standard outputs of reflectance (R) for VIS band imagery, brightness temperature (TB) for the TIR and water vapor bands, and total atmospheric transmittance to control image transparency. To better capture the effects of partial cloudiness in the imagery, IM2FILE blends the separated clear-sky and cloudy output radiances based on the model-derived total cloud cover parameter.
All parameters at this stage remain on the atmospheric model’s original computational grid. IM2FILE can optionally transform the image to geodetic projection and/or map the source grid to a user-defined image size and resolution based on the combination of bicubic and/or 4th order (cubic) B-spline (Freimage, 2009) interpolation methods.

Image files are currently created in PNG, NITF, geoTIFF, and KML formats. PNG files include 3-color (red-green-blue) image data and a transparency (alpha) band. NITF files include an index image with color look-up table and geographic, valid time, and projection tags. The DoD defined GEOPS, GEOLO, MAPLO, and PRJPS NITF data extensions and a text segment are all supported to ensure proper ingest by C2 systems. Figure 2 illustrates the final products in PNG format, with a TIR sensor image on the left and Visible sensor image on the right that indicates the effect of solar angle on the scene.

Figure 2: Infrared (left) and Visible (right) imagery samples with standard background.

4. References