Full Optical Spectrum Hyperspectral Scene Simulation

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***Abstract*-Full optical spectrum (UV to LWIR) hyperspectral scene simulation provides an accurate, robust, and efficient means for algorithm validation and sensor design trade studies. This paper reviews the development of a first-principles, high-fidelity HSI/MSI image simulation capability, dubbed MCScene and demonstrates how the model can be used for sensor design trade studies. MCScene incorporates all optical effects important for solar-illuminated and thermal scenes, including molecular and aerosol scattering, absorption and emission, surface scattering and emission with material-dependent bidirectional reflectance distribution functions (BRDFs), multiple scattering events, surface adjacency effects, and scattering, emission and shading by clouds, for arbitrary solar illumination and sensor viewing geometries. The "world" of the simulation is a cube that encloses a user-definable atmosphere containing molecular species, aerosols, and clouds, and a terrain representing the ground. The sensor spatial and spectral resolution, its location, and the viewing angle are also specified. 3D objects can also be inserted into the scene. A particular strength of MCScene is that a simulation can be data driven. Terrain information can be imported from USGS digital elevation maps. Surface reflectance or emissivity/temperature maps can be derived from collected imagery, thus incorporating natural spectral and spatial texturing into a simulation. Basic features of the model will be discussed and illustrated with a full spectrum simulation for a prototype hyperspectral sensor.**

I. INTRODUCTION

Remote hyperspectral and multispectral imagery (HSI and MSI) of the Earth has proven to be highly valuable for numerous applications, including mineral prospecting, environmental and land use monitoring, and military surveillance and reconnaissance. The quality of the data products depends critically on the accuracy of the atmospheric compensation, surface reflectance or emissivity/temperature retrieval, detection/identification and other algorithms. Thus, there is a need for accurate, robust, and efficient means for algorithm validation. For this purpose, simulated imagery can provide a practical alternative to field measurements, which are typically expensive, time consuming and impractical for covering the full range of anticipated atmospheric and surface conditions.

This paper reviews the development of a first-principles, high-fidelity HSI/MSI image simulation capability [1], dubbed MCScene, that is based on a Direct Simulation Monte Carlo (DSMC) approach for modeling the 3D radiative transport and reports on the extension of this model to include a treatment of the thermal IR (TIR) domain. With this approach, "ground truth" is accurately known through input specification of surface and atmospheric properties, and it is practical to consider wide variations in these properties. The method can treat land and ocean surfaces, effects of finite clouds, and other complex spatial effects, as indicated in Figure 1. The well-known drawback to the DSMC approach is the very large number of trial "photons" needed to achieve an accurate result, leading to very long computation times. However, recent advances in computing speed combined with convenient and affordable parallel processing systems are overcoming this limitation.

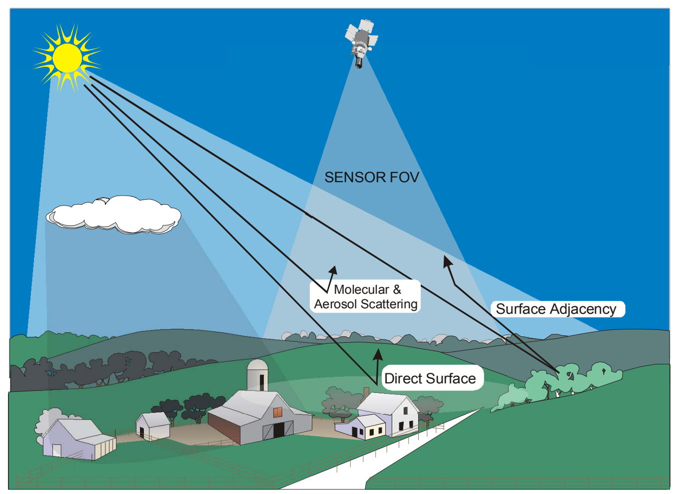

Figure 1. Important radiative transport effects for spectral image simulation, in the reflective spectral domain, highlighting different trial photon trajectories.

The basic DSMC methodology for the reflective spectral domain is described in Section II. This section begins with an overview of the model and includes simulations demonstrating the effects of varying atmospheric visibility. Section III outlines the approach for adding the TIR spectral domain into the simulation tool and presents a sample TIR image. Section IV contains a discussion of future model upgrades and a summary of the paper.

II. REFLECTIVE DOMAIN MODEL

A. Model Overview

MCScene incorporates all optical effects important for solar-illuminated scenes, including molecular and aerosol scattering and absorption, surface scattering with material-dependent

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bidirectional reflectance distribution functions (BRDFs), multiple scattering events, surface adjacency effects, and scattering and shading by clouds, for arbitrary solar illumination and sensor viewing geometries. As shown in Figure 2, the "world" of the simulation is a cube, nominally 50 km on a side that encloses a user-definable atmosphere containing molecular species, aerosols, and clouds, and a base representing the ground. The sensor spatial and spectral resolution, its location, and the viewing angle are also specified. The field of view (FOV) is a finely gridded inner region within the 50 km x 50 km ground area; in Figure 2, it is a 10 km square gridded with 1m^2 pixels. The technique supports surface facets with arbitrary elevations and normals, which can be defined to describe 3D objects as well as terrain.

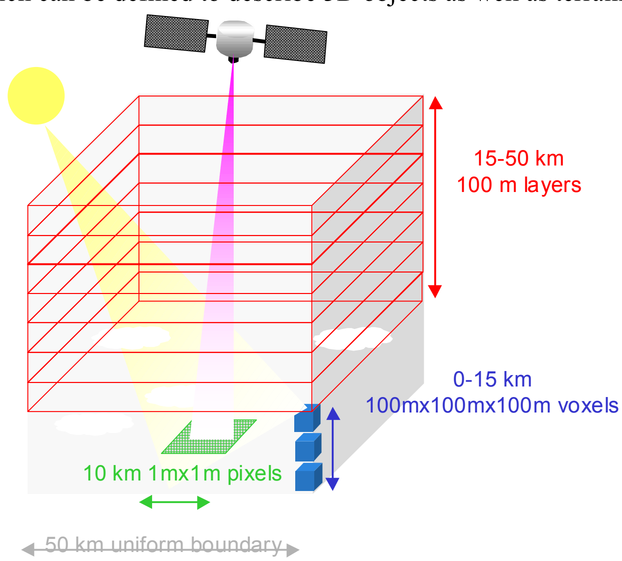

Figure 2. Elements of the scene definition in the simulation model.

Surface reflectance properties within the FOV are assigned on a pixel-by-pixel basis. The area outside the FOV contributes to adjacency effects, i.e., effects due to photons that reflect off the ground and scatter into the FOV[2]. This area is taken to be homogeneous, a simplification that should affect only the edges of the FOV, since the length scale of adjacency scattering is typically ~1 km or less. The reflectance functions for the ground materials are represented as Lambertian or by a modified version of a Walthall surface BRDF [3]. The Walthall representation is computationally simple, is readily sampled, and is based on recent measurements and modeling of crops, soil, calibration surfaces, and roads.

Atmospheric information is stored as vertical profiles indexed to ground position. The atmosphere below ~15 km altitude is divided into 100 m x 100 m x 100 m voxels, whose footprints cover the full 50 km square world. The atmosphere from 15 to 50 km is modeled as a single uniform profile with 100 m layers and no horizontal variability. The atmospheric profiles specify the altitude dependence of extinction cross-sections, scattering cross-sections, and densities for aerosols, clouds, and molecular species.

The image simulation is performed utilizing a backward DSMC radiative transport (RT) technique. (We use the term "backward" Monte Carlo as opposed to "forward" because photons are traced backwards along their trajectories from the sensor to the sun.) The major advantages of DSMC over other scattered radiance techniques are its simplicity, accuracy, and versatility, enabling rigorous modeling of complex 3D effects of clouds, shadowing, adjacency, terrain topography, etc. The major drawback of the DSMC technique is that it is computationally intensive. In the current model, the bulk of the computation time is spent calculating transmittances along the photon paths. Using a fixed integration path length within altitude regions together with nearest-neighbor extinction coefficient data has optimized these transmittance calculations. This optimization, along with a physics-based sampling of the distributions influencing photon trajectories and on-the-fly convergence testing, makes the process efficient enough to generate images at hyperspectral resolution.

In the backward DSMC method, many photons are launched toward the ground, their trajectories are followed, and their contributions to the apparent reflectance are accumulated as a function of pixel position to build up the scene at a given wavelength. Along these trajectories the photons may be scattered by molecules, aerosols, or clouds, they may be absorbed, or they may reflect from the ground. MODTRAN [4] generated optical property databases provide the required spectral scattering and absorption data used in the model. The mathematics of the Monte Carlo sampling of the different atmospheric and surface optical interaction distribution functions that describe the problem physics are discussed elsewhere [1]. A given photon may undergo multiple scattering events. A complete data cube is built up by performing the calculations for many different wavelengths.

Considerable effort was expended to optimize the computational efficiency of the code in order to make execution times reasonable. A typical full hyperspectral scene might involve 200 spectral channels and 10^6 image pixels. Using 10^4 photons per pixel per channel to achieve a 1% statistical accuracy, creating this data cube with the current MCScene model would require about 40 hrs of computational time on a 1 GHz microprocessor. This timing is for a simulation that includes Rayleigh, aerosol, and cloud scattering, and in which photons scatter 6 to 7 times on average. Individual pixels are calculated in a fraction of a second.

B. Image Simulation

A series of calculations were performed to demonstrate the utility of the simulation software for generating a realistic, high-spatial-resolution image. The scene construction was based on surface reflectance spectra retrieved from AVIRIS data taken over NASA's Stennis Space Flight Center. The retrievals were performed using the atmospheric compensation code of Adler-Golden [5], the results are in good agreement with ground truth spectra and radiosonde water vapor measurements. The atmosphere profiles are taken from MODTRAN's mid-latitude summer model with a rural aerosol; a horizontally uniform atmosphere is assumed. The image size is 512 x 512 pixels, and a pixel size of 3 m, a little larger than that of the actual scene, is assumed. The sensor view is nadir and the solar zenith angle is taken as 30 deg. The calculations were performed at three wavelengths, denoted red, green, and blue (0.44, 0.55, and 0.65 μm, respectively). The area outside the FOV was assigned the average in-scene reflectance (0.073, 0.068, and 0.036, for red, green, and blue, respectively). Figure 3 shows the effect of varying visibility on the apparent reflectance of the Stennis scene with the sensor at 20 km altitude. For comparison, the same scene is also shown without an intervening atmosphere. As the visibility is decreased from 100 to 23 to 5 km, the scene becomes increasingly hazy and the ground becomes more obscured.

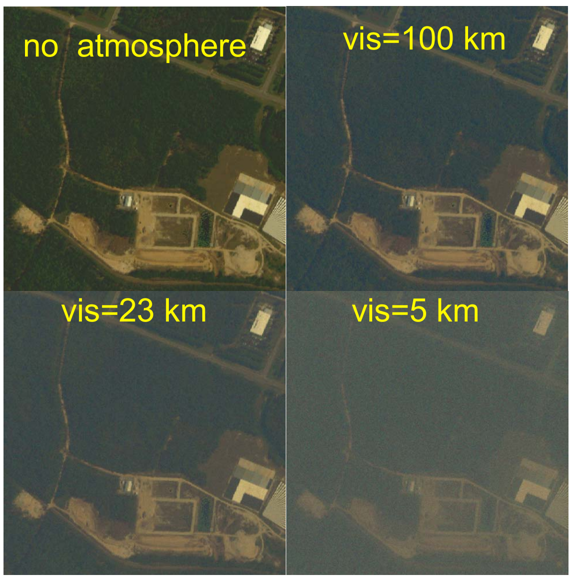

Figure 3. Simulated effect of visibility on Stennis Space Flight Center scene.

III. THERMAL IR SPECTRAL DOMAIN

A. *Direct and Scattered Thermal Emission Formulation*

An approach for incorporating direct and scattered thermal emission predictions into the MCScene simulations has been formulated and validated. The basic idea involves adding the spectral channel emitted thermal radiation to the solar contribution at each radiation event. Thus, one does not compute the thermal illumination only the local emission. The idea is appealing in that it works off the existing trajectory algorithms, it maintains all 3D capabilities, and it solves the RT problem over HSI spectral channels without explicit wavelength sampling. The major challenge of the proposed approach is to rigorously define an in-band emissivity at radiation events. Monochromatically, the emissivity is a local function of position, but the in-band contribution to the thermal radiance depends on the photon history.

The integration of the thermal emission model into the MCScene requires access to spectrally-convolved, path-dependent molecular transmittances and their column density derivatives. In the MCScene software package, the MODTRAN4 atmospheric model is used to compute narrow bin molecular absorption transmittance databases. The MODTRAN4 band model accurately determines the molecular absorption in 1 cm-1 spectral bins from temperature-dependent band model parameters. These parameters specify the total strength of the molecular transitions centered within the spectral interval, the effective number of lines, their spectral width, and the strength of neighboring lines. A mapping from path properties to transmittance is defined by assuming that the lines are randomly distributed in the spectral interval, a good approximation for narrow spectral bins. The 1 cm-1 band model provides spectral resolution sufficient for characterizing the channel response function of current Vis-SWIR HSI systems. In the thermal regions, next-generation HSI systems require finer spectral resolution, which is provided by the 0.1 cm-1 band model found in the next generation of the MODTRAN model [6].

B. *Sample Thermal Imagery*

We have developed a procedure for simulating a realistic hyperspectral or multispectral reflectance cube at arbitrary wavelengths from the visible through LWIR using a Vis-SWIR hyperspectral image as a template. The result can serve as the starting point for a radiance image generator such as MCScene. The procedure involves assembling the cube from a set of full spectral range material spectra weighted by fractional abundances derived from an AVIRIS Vis-SWIR image. Since both the abundances and material spectra derive from real (though separate) measurements, the simulated cube should have spatial and spectral properties similar to that of an actual scene.

Figure 4 show the results of MCScene simulations using the MTI band passes for the Visible, MWIR and LWIR [7]. The sun was placed in the west of the image (left hand side) for the visible imagery and nearly overhead (11:15 AM local time) for the thermal image. In both simulations the sensor was placed at 20 km altitude and a nadir viewing geometry.

In another example, an industrial complex has been added to the full spectrum scene described in section above. The industrial site contains elements found in typical power generation plants including tall smoke stacks, large cement buildings, large steal and aluminum roofed buildings, roads, parking lots and steel pipes and storage tanks. Figure 5 shows a series of shadow images for the scene. Shadow images are created using a reflectance of unity and digital elevation map (DEM) with the added industrial complex. The images are for times near dawn and dusk for the Virgin Mountains during the month of April. The dawn and dusk scenes are dominated by long shadows that run from east to west or west to east, respectively.

Simulations for a sensor-viewing nadir from 20 km altitude with 50 km visibility and dusk lighting conditions are shown in Figures 6 and 7. Figure 6 is an RGB radiance image using wavelength channels of 10.55, 9.5, 8.5 μm. Representative spectral signatures are shown in Figure 7 for sand and two man-made materials, one of which is highly reflective. The radiance spectra contain a large ozone feature due to transmission losses through the atmosphere, as well as, significant water and carbon dioxide absorption features. The reflective man-made material also shows significant spectral structure due to the reflected downwelling term.

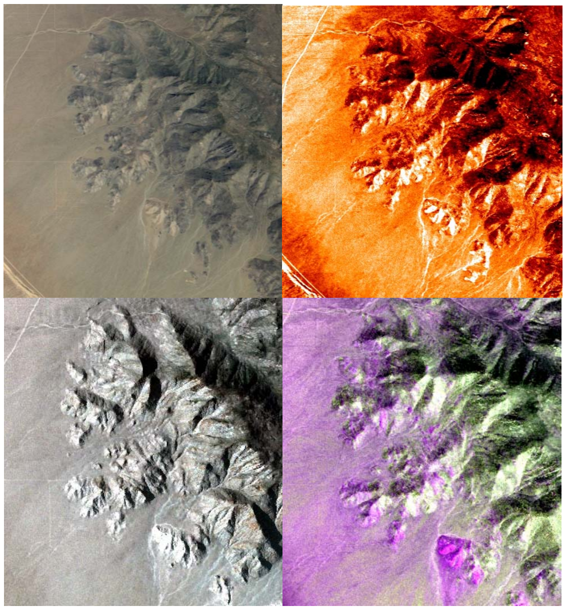

Figure 4. RGB composite (top-left), and derived temperature map (top-right) from an AVIRIS scene of Virgin Mts., NV. The temperature map, temperature increases from dark red to white. MCScene simulations for the Virgin Mountains using MTI bands with the RGB color composite on the bottom left and a color composite for one MWIR (Blue) and two LWIR (Green and Red) bands on the bottom-right.

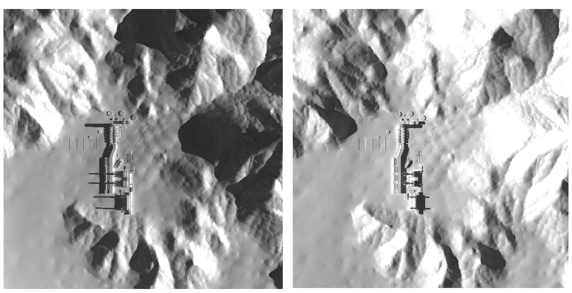

Figure 5. MCScene shadow simulations for the Virgin Mountains with an industrial site added to the scene. Images are shown for times near dawn (left), noon (middle) and dusk (right).

IV. SUMMARY

A practical, first-principles simulation model for hyperspectral or multispectral imagery has been developed based on a Direct Simulation Monte Carlo (DSMC) radiative transport approach. The code, named MCScene, has been successfully validated through comparisons with exact scattering calculations, and its utility has been demonstrated in some initial applications to remote sensing problems. Reasonable computation times are obtained on a personal computer. The performance will improve as processor speeds increase and multi-processor (i.e., parallel processing) systems become commonplace. The current capabilities of the simulation code are unique and state-of-the-art, and are highlighted by the use of a rigorous radiative transport approach from the UV to the LWIR, a full 3D treatment of the atmosphere, including finite clouds, surface BRDFs, and a faceted surface description incorporating surface elevation and 3D objects.

Figure 6. RGB Radiance Image Showing Part of the Industrial Site using spectral channels of 10.55, 9.5, and 8.5 μm for an observer at 20 km altitude.

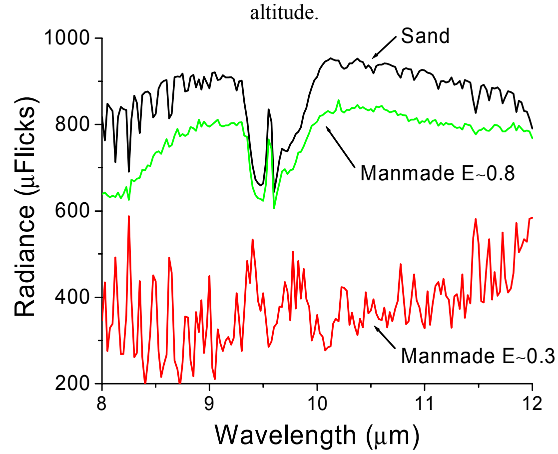

Figure 7. Spectral Radiance Signatures for Three Pixels in the Scene shown in Figure 7.

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