Weather Effects and Modeling for Simulation and Analysis

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Abstract

In the past, the US Army developed the Electro-Optical Systems Atmospheric Effects Library (EOSAEL) [1, 2, 3] as analysis tool to investigate and predict impacts of weather on EO systems. This Tri-Service effort has also been extended to NATO countries through collaboration in several research study groups. As new tools for simulation and analysis are developed to support increasingly sophisticated weapons systems, the US Army in collaboration with the Air Force and Navy has been developing a new generation of tools for this support mission. One of our current efforts is the Weather and Atmospheric Visualization Effects for Simulation (WAVES) series of models. These models are designed to increase our analysis and simulation capabilities through both more sophisticated treatment of complex weather conditions as well as supporting imaging and image modification tools.

Historically, analysts have wanted "one number" effects for weather impacts; future developmental systems will need to be modeled from a physical basis that implements the real impacts of weather on notional systems. Imaging sensors must be able to deal with complex targets, backgrounds and camouflage embedded in an inhomogeneous atmosphere. Truly robust systems require testing in all extremes and variations of weather and climatic conditions, testing that can only be carried out through physics based simulations. The WAVES tools are designed to immerse an imaging system in a consistent atmospheric environmental simulation that allows investigation of illumination, shadow, radiance, transmission and turbulence effects on sensor and algorithm performance.

This presentation will describe the existing models in the WAVES toolbox, their interactions with other environmental models and an outline of the future research directions we will be undertaking.

1 Introduction

Historically the US Army has developed and supported the Electro-Optical System Atmospheric Effects Library (EOSAEL) as the tool to address impacts of the environment on weapons system performance. Development and support for the EOSAEL has been ongoing since the late 1970's. From the beginning this toolkit was envisioned (and implemented) to support Army, Naval, and Air Forces requirements for transmission and visibility calculations in the near earth environment in the presence of battlefield debris. During the design and implementation for the original EOSAEL computer capabilities of the target users forced a focus on straightforward single line-of-sight calculations. Local weather was represented by a single representative vertical sounding that represented the battlefield. Very high resolution effects such as turbulent structure in smoke plumes could not be exploited by the customers, and was not included.

Many EOSAEL models make a calculation of the point-to-point transmission between a target and a sensor. This arises from the way EOSAEL models treat obscurants in the atmosphere as a series of effects that can be superimposed. For instance, if there are several smoke clouds, some vehicle dust, and low stratus clouds we would perform a helicopter to tank

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line-of-sight calculation as follows:

1. Use LOWTRAN [4] (now replaced with MODTRAN[5]) to calculate the end-to-end transmission caused by the molecular extinction along the path.
2. Use XSCALE to calculate the end-to-end transmission due to extinction by fog and natural clouds.
3. Use COMBIC to calculate the end-to-end transmission due to smoke and dust clouds in the path.
4. Calculate the total end-to-end transmission as the product of these three terms.

If we are dealing with the effectiveness of a laser device instead of a broadband device, we replace the LOWTRAN/MODTRAN calculation with the EOSAEL LZTRAN model for laser transmission. the analyst would then typically compare this total transmission coefficient to a threshold value to determine if target acquisition or lock-on could occur.

Some radiance effects have been addressed in the EOSAEL, both for finite clouds as isolated effects and for the atmosphere as a whole as represented the sky-to-ground ratio calculation in FASCAT.

The EOSAEL included a climatology module, CLIMAT, providing weather driven climatology. Limited regions were originally available, though now North and South America; Europe; Southwest, Southeast, and Northeast Asia have been compiled. Missing from this collection are Central Asia, Africa, and Australia. Figure 1 shows the regions of the world that currently have climat summarys available. The CLIMAT statistics have been generated from one viewpoint, highly focused on aviation related ceilings and cloud cover, visibility, and precipitation. The use of these climatologies for electro-optic prediction has the drawback that the EO propagation statistics calculated from average values of weather variables is not the same as the average EO propagation calculated from complete weather observations. It is also difficult to understand the connection between extreme weather events and the resulting EO propagation expected.

Figure 1: Regions of the world for which CLIMAT abstracts have been built

After 20 years of support, the EOSAEL is now being commercialized[6]. ARL research is entering a new phase aimed at support of more sophisticated EO simulations.

A new paradigm is being started with the development of WAVES (Weather and Atmospheric Visualization Effects for Simulation) which is designed to support the same part of the battlespace, near earth (surface to 5–12 km AGL) tactical encounters (5–20 km on a side) area. WAVES has been developed from the ground up to represent inhomogeneous 3-D atmospheric effects calculations [7] for imaging sensors.

WAVES [8] has been developed to extend the problems that can be solved using traditional solutions such as MODTRAN.

This new suite of models must support imaging, through complex atmospheres including both complex natural clouds as well as through battlefield effects. WAVES produces 3-D fields of radiance that treat transmission and radiance as equal contributors to imagery. WAVES will modify computer generated visualizations and modify real images. We will of course draw from our past experience and models and interface to the best available supporting models.

Again, our audience is still diverse and trying to answer many different questions, we can not supply only a single answer. We need to develop a series of tools for systems designers and analysts to use. EOSAEL had and WAVES will inherit the army perspective of close to the ground, in the dirty battle-

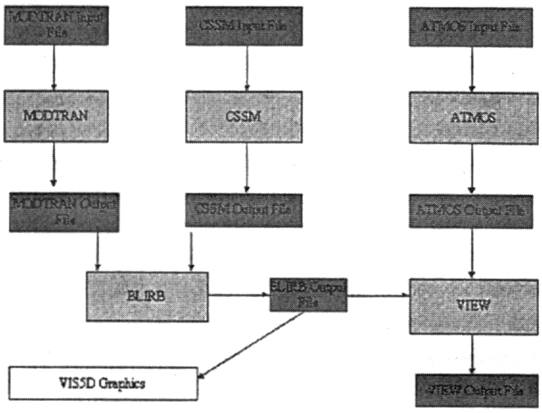

Figure 2: Organization of the WAVES components.

field. The 3-D grid of atmospheric illumination information computed by WAVES can be used for simulations supporting testing and evaluation, analysis, planning, training, and research.

2 WAVES

WAVES is a toolkit of several modules that will operate together. It tries to answer the question of what a sensor would see under given weather conditions, or how a sensor view would have been different if the weather had been different.

The ability to substitute different weather conditions and simulate effects allows testing and development to proceed at one location with confidence that we can predict operation at other locations with different weather. These capabilities also can be used to support mission rehearsal and contingency analysis.

It is integrated with other DoD modeling projects such as the US Air Force's MODTRAN[5] and Cloud Scene Simulation Model (CSSM)[9]. The relationship between the various components of WAVES is illustrated in figure 2.

The highest fidelity representations are photorealistic image transformations. These can include both transformations of actual field data to represent other weather conditions or accurate rendering of computer generated images.

A lower fidelity level is represented by statistical sampling of measurements for grid based wargames and development of integrated Weapons-Sensor-Target-Weather (WSTW) effectiveness parameters. Representing the WSTW effectiveness as a decomposable factor problem, especially at the level required for accurate simulation based acquisition, remains an open problem. We hope that WAVES will give analysts some of the tools necessary to approach this problem from a fundamental physical understanding.

Finally, a simulation or engineering tool may want to look at the fundamental quantities such as the fluxes to integrate with other models.

2.1 Image Modification

Our most ambitious goal is modeling a sensor looking through the atmosphere seeing targets and backgrounds. When modifying an image to account for atmospheric effects we treat the pixels in the original image as sources that propagate to a detector. Along this journey some of the energy is removed before reaching the detector by extinction; molecular absorption and scattering, aerosol absorption and scattering. Also, energy in the atmosphere along the path joins in the journey to the detector; thermal emission, forward scattering by large aerosols, large angle scattering of fluxes in the atmosphere into detector.

The geometry used in WAVES for image modification is represented by a vector from observer to target, $\vec{R}$, for the pixel, (a, b).

$$\vec{R} = \vec{R_t} - \vec{R_o} = \text{observer to target path vector} \quad (1)$$

The propagation of energy from the target pixels to the observer where it is represented as image pixels, I_{ab}, is described by,

$$L_{ab} \times T(\vec{R}) + P(\vec{R}) = I_{ab} \quad (2)$$

with,

$$L_{ab} = \text{ source radiance} \quad (3)$$

from the scene element that is at range R. Where,

$$T = \text{transmission}, \tag{4}$$

and,

$$P = \text{path radiance}. \tag{5}$$

Each pixel in an image has a slightly different θ and ϕ, that are simply related to their location in the image. In addition, each pixel has a range from the observer that is a complex function of the details of the terrain and geometry of the objects in the scene.

The transmission and path radiance will be computed for a sparse sampling of $\vec{R}_o$, θ, ϕ, and R. The sampling of θ, ϕ, and R represents an observer-centric sampling of target locations. Alternatively we could calculate all possible cell center to cell center lines-of-sight

2.2 Line-of-Sight Parameters

For a line-of-sight the range dependent transmission and path radiance values are calculated by the VIEW module of WAVES.

$$T(R) = e^{-\int_o^{\vec{R}} \tau(\vec{R})\, dR} \tag{6}$$

$$P(R) = \int_o^{\vec{R}} T(\vec{R}) F(\vec{R}, \hat{\Omega})\, dR \tag{7}$$

Within WAVES and VIEW these integrals are replaced by summations through the gridded volumes along the lines-of-sight and tabulated by range, and azimuth and elevation angles.

Thus we represent extinction by $\tau(\vec{R}_{i,j,k})$ and compute fluxes as the directional quantities $F(\vec{R}_{i,j,k}, \hat{\Omega}_n)$. Our representation of space is a grid of 3 spatial dimensions, indexed by the values i, j, k augmented with discrete direction vectors indexed by n.

2.3 3 Dimensional Radiative Transfer

The 3-D Radiative Transport portion of WAVES is the Boundary Layer Illumination and Radiation Balance (BLIRB) model. Its task is to take a description of the inhomogeneous optical properties of a small region, use boundary conditions from MODTRAN, and then solve for the 3-D radiant fluxes at all locations and directions[7]. The model calculates local extinction coefficient, direct solar flux, and directional diffuse fluxes using a discrete ordinates approach to multiple scattering.

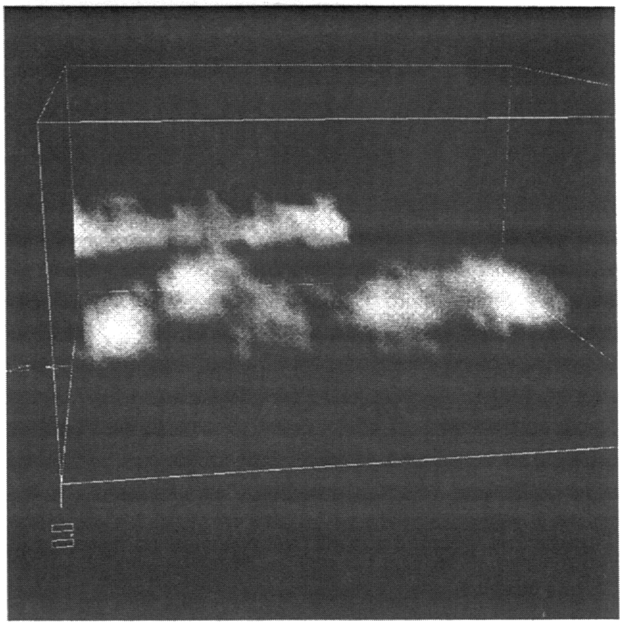

Figure 3: The CSSM cloud field.

The local optical properties are derived from MODTRAN molecular extinctions, aerosol haze layers, 3-D cloud structures from CSSM, and will include in the future 3-D smoke effects from models such as COMBIC and STATBIC. Figure 3 shows a volumetric rendering of a CSSM cloud field for use in WAVES. Figure 4 shows the "surface" of the same cloud.

The result of running BLIRB is similar to a radiosity calculation from computer graphics, we know what the directional fluxes are everywhere, and we can embed small objects within this volume and calculate what light falls upon them. We can also perform calculations to determine the shadows these perturbing objects would cast.

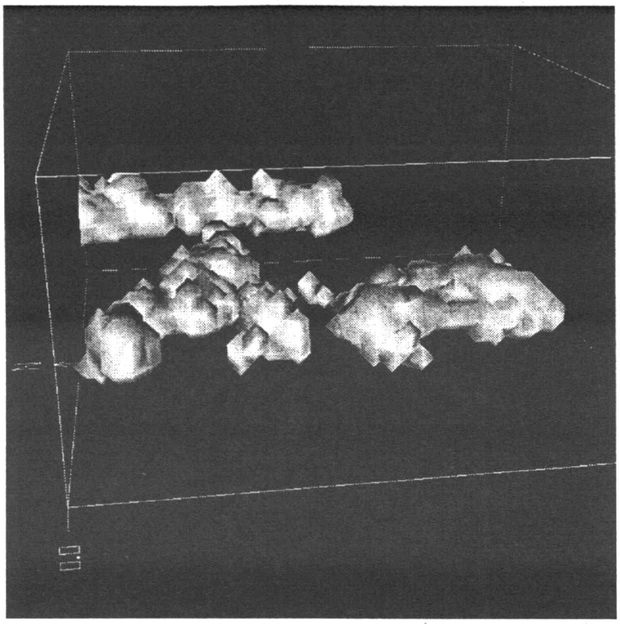

Figure 4: The cloud surface.

2.4 Illumination

In many cases we require knowledge of the energy illuminating a surface. For proper rendering of scene elements we need to know both the intensity of the direct solar component, that casts a shadow, and the diffuse fluxes, that fill in the shadows. Figure 5 shows the direct solar illumination beneath the cloud field. Figure 6 shows a vertical slice of the direct solar radiation and the complex structure of the cloud shadows. In most cases the magnitude of the diffuse component will vary based on both azimuth and elevation angle of the surface being illuminated. Figure 7 shows the downward diffuse flux under the cloud field created by reflection from the cloud. Figure 8 shows the downward diffuse flux under the cloud field created by transmission through the edges of the cloud. Figure 9 shows the upward diffuse flux above the cloud field created by reflection from the cloud.

In WAVES, these quantities are naturally calculated in the discrete ordinates methodology, and reported for the ground surface. This illumination at the surface (at all wavelengths) is also a quantity use-

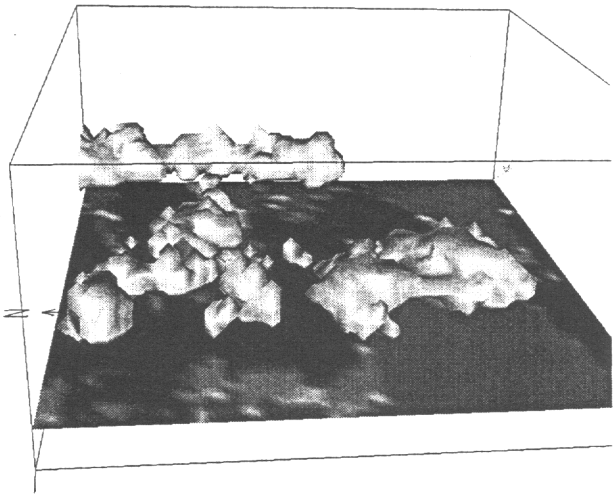

Figure 5: The direct solar surface illumination.

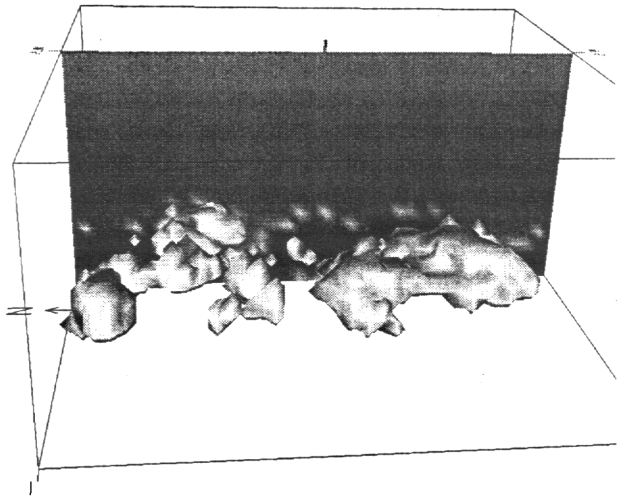

Figure 6: The direct solar illumination for a vertical slice.

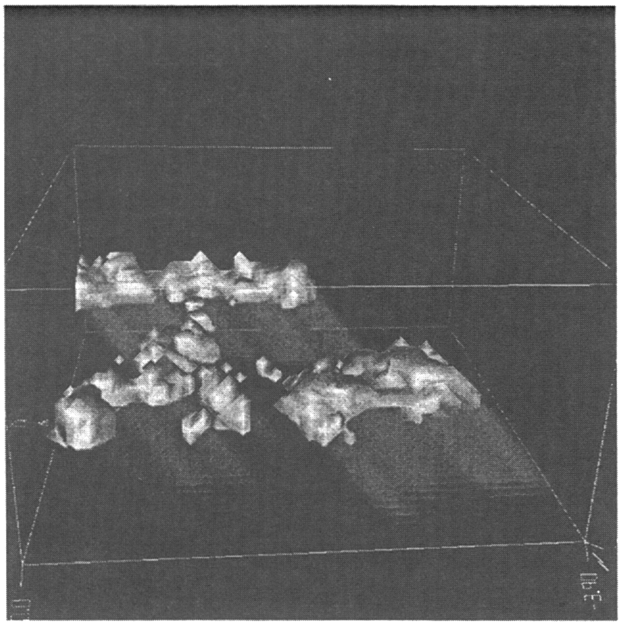

Figure 7: A volumetric rendering of the diffuse illumination in forward direction. Stream 1

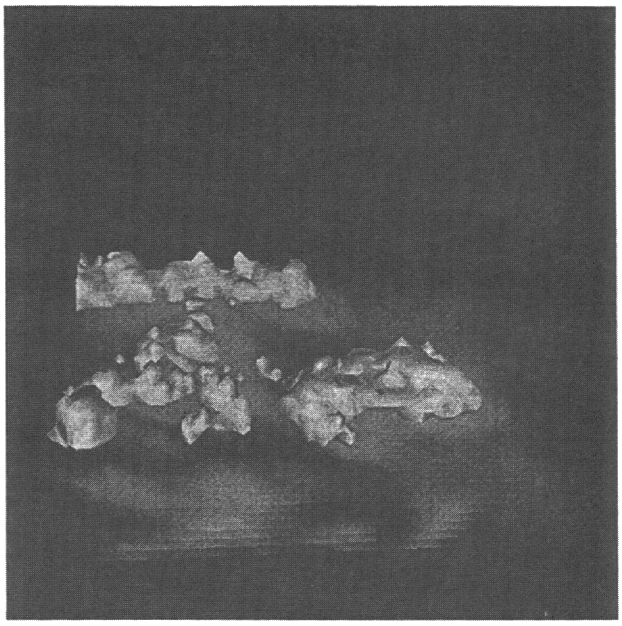

Figure 8: A volumetric rendering of the diffuse illumination in forward direction. Stream 2

ful for thermal modeling of targets and backgrounds.

Proof of concept implementations for searchlights and flares have been implemented in BLIRB. If needed, other sources of artificial illumination can be incorporated.

2.5 Turbulence

ATMOS is used to calculate the vertical profile of the refractive index structure parameter, C_n^2, assuming horizontal homogeneity. This turbulence calculation is made using easily obtainable meteorological parameters[10] The refractive index structure parameter is used in a modulation transfer function (MTF) that is folded into the propagation calculations to give time-averaged effects, or blurring, from turbulence. Real time fluctuations due to turbulence are not computed using this model.

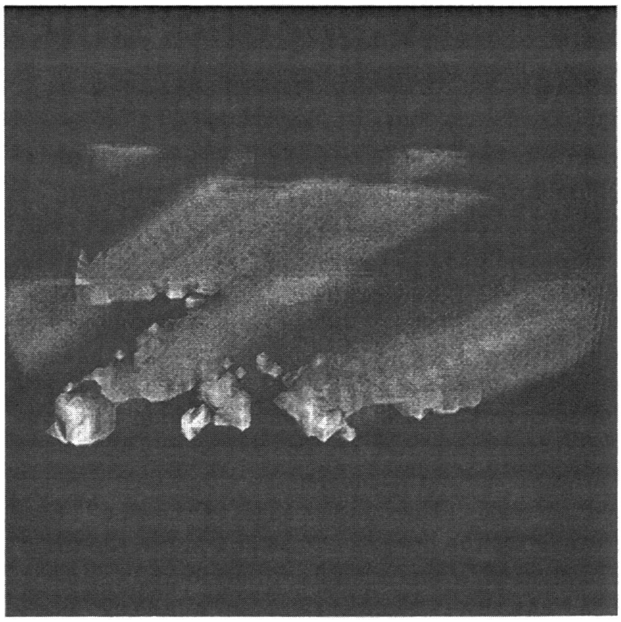

Figure 9: A volumetric rendering of the diffuse illumination in forward direction. Stream 5

3 Additional Capabilities

3.1 COMBIC

COMBIC is an existing EOSAEL model that creates cloud skeletons and optical properties descriptions for artillery explosions, smoke munitions and vehicle dust[11, 12]. It has historically been used only to provide line-of-sight transmission calculations.

There are two fundamental ways we could treat smoke clouds in WAVES. The first uses superposition of optical properties from the COMBIC output with the existing optical properties describing our space. We then would solve the 3-d radiative transfer and obtain a full solution.

The second way is to perform the solution of the natural environment and treat the smoke as a perturbation of the natural state. In this case the smoke is treated much like a vehicle that doesn't have a major impact on the radiative properties of the space. We would then add the smoke, calculate the shadows cast by the smoke, and use an external model to add scattering from the smoke.

For one or two isolated smoke plumes the second method is appealing. When we consider what would happen in a major battle with hundreds or thousands of smoke plumes, we realize that the smoke could dominate the illumination near the ground and only the first modeling approach permits continuous and consistent change from no smoke, to all smoke.

3.2 STATBIC

STATBIC[13] is a methodology for replacing the smooth Gaussian plumes used in the COMBIC model with volumetrically textured smoke density distributions that match the turbulent effects seen in actual smoke clouds. Our intention is to use STATBIC to produce realistic textures of smoke and dust plumes in our integrated 3-D simulation suite.

4 Other Models

In order for WAVES to be integrated with other parts of large simulations it must use weather data that is consistent with the description used by other models in the simulation. There are several ways of doing this, the most useful is to integrate WAVES with other tools being used in the simulators. Examples are the Weather IN Distributed Simulations/Total Atmosphere Ocean Server (WINDS/TAOS) used in the JSIMS program, and the Distributed Environmental Effects Manager/Dynamic Information Architecture System (DEEM/DIAS) used in the JWARS program.

Also, the output of WAVES needs to be available for Object-Oriented simulators to extract and access. We are currently developing a toolkit that will include APIs to allow HLA simulations access to both the WAVES results and the individual WAVES tools.

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