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6. AUTHOR(S)
J. Yen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152-5000

San Diego State University Foundation
5300 Campanile Drive
San Diego, CA 92182

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FINITE CLOUD-LASER PULSE INTERACTION MODELING

John Yen
Naval Ocean Systems Center
San Diego, CA 92152 (619) 553-6205

ABSTRACT

Simplified cloud models are currently utilized in the simulations of space-based laser communications. The Naval Ocean Systems Center is developing a database incorporating the interactions of a cloud of finite extent and a visible light pulse originating in space. We are generating such a database with Monte Carlo simulations of light photons illuminating a finite cloud. The database will contain information on the surface radiation intensity profiles and the temporal pulse stretching resulting from passing through the finite cloud. This database can be accessed to estimate the probable signal strength and the maximum allowable data rate when communicating with a pulsed laser through a configuration of several finite clouds situated above the target area. Possible extensions of this finite cloud effort, such as interacting finite clouds and structured clouds, are discussed.

1. INTRODUCTION

The Naval Ocean Systems Center (NOSC) in San Diego, California, developed a computer model simulating the interaction of a visible light pulse originating from space and a cloud of finite extent in support of the Satellite Laser Communications (SLC) Program. Currently, submarines cannot receive detailed information at operational depths and must remain near the surface, increasing their detection risk, to use their high data rate links. SLC was developed to address this problem by taking advantage of the sea water blue-green absorption window (Karp, 1976). With a space-based laser, SLC can provide a one-way satellite downlink to submarines remaining at operational depths with a moderate but acceptable data rate not currently available. Such a laser communications system requires realtime control of the laser beam divergence in order to optimize coverage of the delivery area with minimum laser power output.

The transmission characteristics of the laser beam depend on both the optical and the physical properties of the clouds between the satellite and the submarine operating area. One practical method to determine cloud properties in realtime is to obtain and analyze digital images from a satellite-based detector. An aspect of satellite imagery cloud characterization is that real clouds have finite extent. Finiteness effects must be understood if cloud radiances as seen in satellite images are to be converted to estimate the spatial distribution of pulse signal-to-noise ratio beneath the cloud fields.

Most cloud layers show structure and may be broken into discrete clusters, and the brokenness is especially pronounced near the boundaries of cloud decks. The radiative profiles of structured clouds will differ from those of planar clouds, showing distinct directionality depending on the illumination angle. This is especially true when an image pixel only partially covers a cloud. Then the emissions of cloud sides become highly significant. Strong cloud side emissions can mislead by making the cloud appear thicker or thinner than it is (by changing the observed brightness), distorting the cloud parameters used in cloud characterization schemes. McKee and Cox (1974 and 1976), McKee and Klehr (1978), Reynolds et al (1978), Harshvardhan and Weinman (1981), Schmetz (1984), Coakley and Davis (1986) and Kobayashi (1988) are among the many sources available discussing finite cloud interactions with sunlight, a constant source.

2. MODEL

Because the SLC downlink consists of short laser pulses passing through clouds into the sea, it became necessary to study the interaction of a light pulse with a finite cloud and determine the distortion effects, both spatial and temporal, induced by the passage though the cloud. This is most important with non-homogeneous cloud layers and structured clouds. The distortions experienced through a cloud of finite extent depend on the optical thickness, cloud dimensions, the source direction and the observation geometry. The optical thickness (τ) of a cloud is defined here as the vertical cloud physical thickness divided by the mean free path between scatterers (Bucher, 1973).

Our finite cloud model is a straight-forward Monte Carlo simulation of many individual light photons travelling independently through a parallelepiped cloud of operator-specified dimensions and optical properties (see Yen, 1989, and Waldman, 1989, for particulars). While a Monte Carlo model is undoubtably more accurate, models approximating planar cloud layers use less computer time and compare reasonably well for most cases. Thus, it would be expedient to use planar models until a sufficiently complete finite cloud database is compiled.

The model simulates a plane-parallel pulse incident at a specified angle on up to three faces of the parallelepiped cloud (the sides labelled X-, Y- and Z- in Figure 1). Within the cloud, the path of a photon is determined by randomness applied to the mean collision path length (Poisson) and the scattering cross-section (Henyey-Greenstein) for the new scattering direction. Microphysical properties of clouds, such as drop size distribution, liquid water content and aerosol content, are incorporated in the optical thickness, although the effect of each component itself is not now known with certainty. At each collision, the photon position is transformed into a new coordinate system, then transformed back into the objective frame after emergence. The photon thus travels through the cloud, experiencing absorption-free scattering collisions, until it exits one of the cloud faces.

3. RESULTS

When a photon exits the cloud, its trajectory is computed to determine whether its path crosses two imaginary target areas, one on the ground and one above the cloud. Each target area consists of a square array of 101x101 pixels (with each side set to 20 km by default, while the cloud sides are usually set at 1 km) centered on the cloud center. A pixel counter is incremented whenever a photon is projected to have pass through the area covered by that pixel. These stored target arrays will then represent the radiation intensity profiles from a finite cloud above and below the cloud. The ground target array will be the spatial signal distribution for ground reception, while the overhead target array describes the upwell profile.

The upwell profile helps to characterize the cloud type or structure in satellite imagery with non-homogeneous clouds. An example of the graphic output is shown in Figure 2, where the pulse is vertically incident on the cloud from above. From the stored data array, one can take cross-sections (Figure 3) to

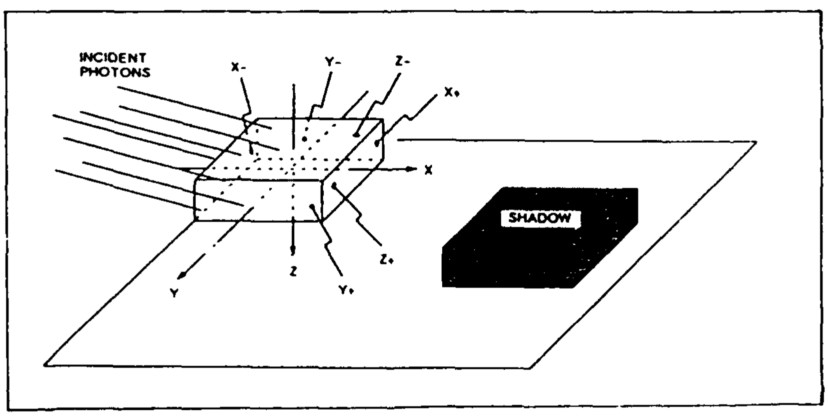
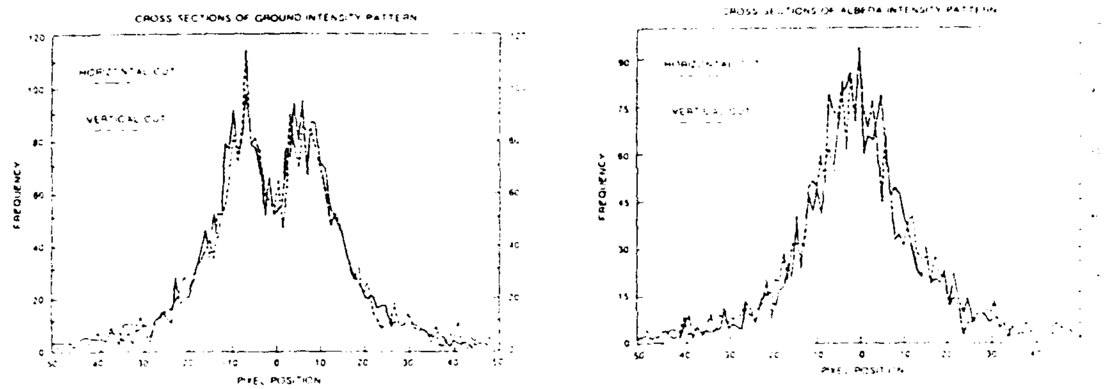


FIGURE 1. Finite Cloud Model Schematic

a) Ground Pattern b) Overhead Pattern

FIGURE 2. Radiation Intensity Patterns (Vertical Incidence: $\theta=0^\circ$ and $\phi=0^\circ$)



a) Ground Cross-section b) Overhead Cross-section

FIGURE 3. Radiation Intensity Profiles (Vertical Incidence: $\theta=0^\circ$ and $\phi=0^\circ$)

analyze the radiation distribution. As expected, the upwell shows a normal distribution (Figure 3b), mostly "reflection" from the cloud top. The ground target shows that the radiation distribution is most intense about the sides of the cloud (see Figures 2a and 3a), that is, photons are more likely to exit cloud sides in downward directions than going completely through the cloud to exit the bottom face given a significant cloud optical thickness (τ=20). This implies that some regions under the cloud can receive stronger signal than with a clear sky. There is a constant signal level under a planar cloud layer.

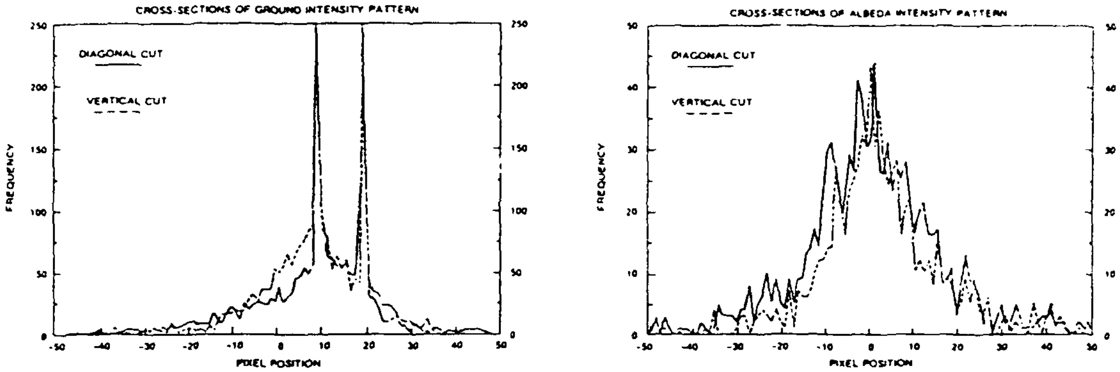
Figures 4 and 5 are corresponding results for when the three incidence faces are illuminated equally. The upwell is skewed in favor of the "forward" direction (Figure 5b), which would account for the so-called reflection from the cloud top. The downwell shows a much more obvious directionality in the edge effect. Since photons entering the cloud near an edge have a strong likelihood passing through that corner of the cloud without being scattered, they will continue in their original path and form a geometric figure on the ground outlining the cloud boundaries (Figure 4a).

Pulse stretching through clouds is important because it determines the maximum data rate of the laser link. When the ground receiver is not in the cloud's shadow, the "direct" signal from the laser beam should be overwhelming, so that pulse delays for receivers within cloud shadows should receive more attention. A 3x3 array is set up in the cloud shadow (or anywhere on the ground for that matter). When a photon passes through one of the pixels, its delay (relative to the direct path from beam plane) due to the cloud is computed and

a) Ground Pattern

b) Overhead Pattern

FIGURE 4. Radiation Intensity Patterns (Angled Incidence: θ=54.7° and ϕ=45°)



a) Ground Cross-section

b) Overhead Cross-section

FIGURE 5. Radiation Intensity Profiles (Angled Incidence: θ=54.7° and ϕ=45°)

tabulated. Figure 6 shows the pulse delay distribution for vertical incidence angle. Note that the pulse delay curve is not smooth even with 500000 incident photons because of the small number of photons (818) actually reaching the small delay target. Simulations performed to date resulted in pulse delays of 100 μs or less.

4. CONCLUSIONS

The emission profile of a finite cloud, as compared to a planar cloud layer, tends to reduce the upwell in favor of horizontal and downward emission. Therefore, the angle of observation can greatly affect the cloud brightness observed. This complicates cloud characterization algorithms unless finiteness is understood and taken into account. In view of the importance of the observation angle, the model has been modified to record the intensity profile from all sides of the cloud (see Figures 7 and 8). However, the collection of a database of such cloud profiles is left to the future.

For statistical validity, it is common to use tens of thousands (hundreds of thousands in some cases) of photons in the Monte Carlo simulations, which is rather time-consuming on a personal computer. A possible solution is the intensity reference method, which sums the probability of hitting a receiver on the ground for each photon at the last collision before it exits the cloud (Waldman, 1989). This method requires a smaller number of photons to achieve the same degree of statistical validity as the simple Monte Carlo, since each exiting photon contributes to the total delay distributions.

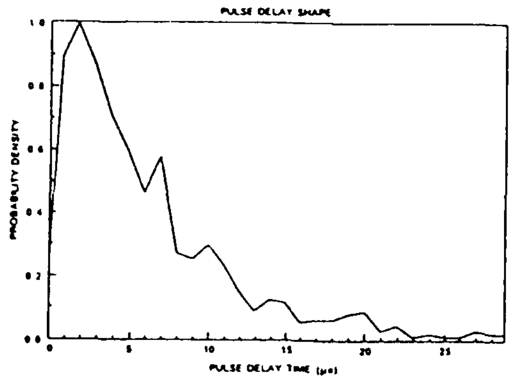
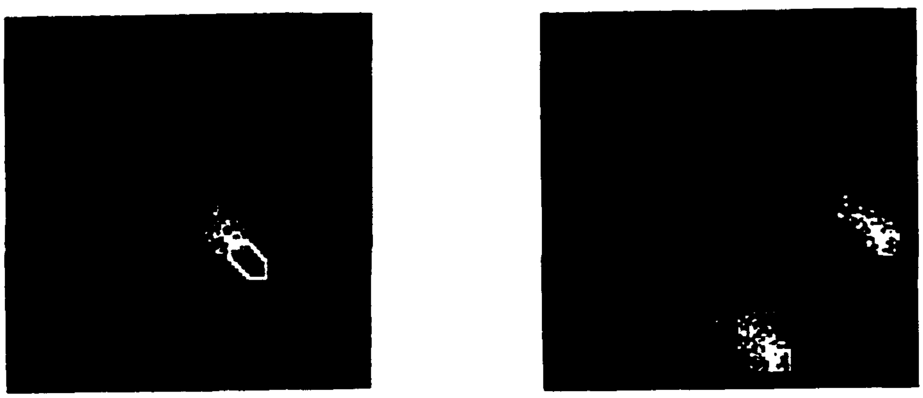
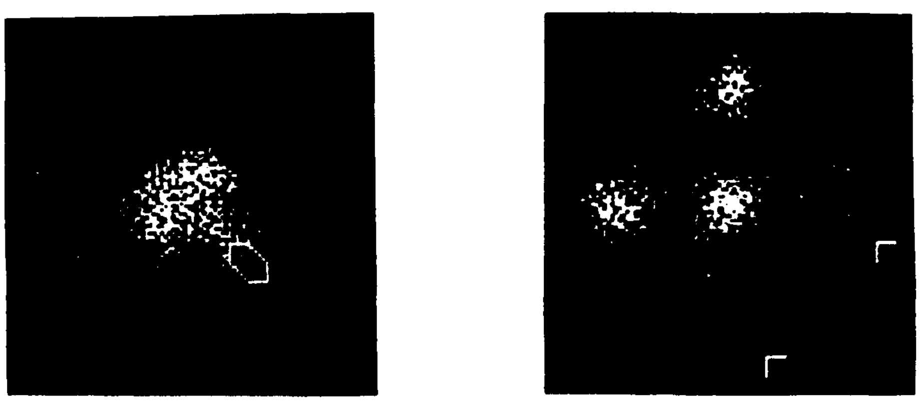


FIGURE 6. Cloud Transmission Pulse Stretching
500000 Trials, 818 Pulse Photons, Maximum=111
τ=20, θ=0°, ϕ=0°, X=Y=10 km, Z=1 km, H=1 km



a) Ground Pattern b) Overhead Pattern

FIGURE 7. Full-Coverage Profiles (Regular Cloud: τ=20, θ=54.7° and ϕ=45°)



a) Ground Pattern b) Overhead Pattern

FIGURE 8. Full-Coverage Profiles (Thick Cloud: τ=90, θ=54.7° and ϕ=45°)

When a database of cloud profiles has been collected, work should proceed on studying the combined profile of a receiver under an array of non-interacting finite clouds. The effects of cloud-to-cloud interactions on receiver signal distribution should be studied. Additionally, several finite clouds should be combined to form a structured cloud to better understand complex clouds.

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