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MULTIDIMENSIONAL MODELING OF ATMOSPHERIC EFFECTS
AND SURFACE HETEROGENEITIES ON REMOTE SENSING

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The overall goal of this project is to establish a modeling capability that allows a quantitative determination of atmospheric effects on remote sensing including the effects of surface heterogeneities. This includes an improved understanding of aerosol and haze effects in connection with structural, angular, and spatial surface heterogeneities. One important objective of our research is the possible identification of intrinsic surface or canopy characteristics that might be invariant to atmospheric perturbations so that they could be used for scene identification. Conversely, an equally important objective is to find a correction algorithm for atmospheric effects in satellite-sensed surface reflectances.

Our technical approach is centered around a systematic model and code development effort based on existing, highly advanced computer codes that were originally developed for nuclear radiation shielding applications. Computational techniques for the numerical solution of the radiative transfer equation were adapted on the basis of the discrete-ordinates finite-element method which proved highly successful for one- and two-dimensional radiative transfer problems with fully resolved angular representation of the radiation field.

Results of the initial phases of our research project, namely, the implementation and verification of computer codes and modern atmospheric data bases, have been published and proved highly successful. In the next step, a coupled atmosphere/canopy model was developed that allowed us to perform a sensitivity analysis and to quantify how satellite-sensed spectral radiances are affected by increased atmospheric aerosols, by varying leaf area index, by anisotropic leaf scattering, and by non-Lambertian soil boundary conditions. Our numerical results allow the following conclusions:

1. Atmospheric perturbations are the major contributors to Landsat MSS bands 1 and 2 (visible), while they play only a minor role in MSS bands 3 and 4 (near-IR) for remotely sensed images of vegetative surfaces. The Kauth-Thomas greenness parameter is found nearly proportional to the atmospheric optical depth over uniform vegetative surfaces.
2. The inclusion of anisotropic leaf scattering characteristics in our canopy model is significant to explain reflectance measurements directly above the canopy but produces only negligible effects on satellite-measured data above the atmosphere at nadir.

3. Non-Lambertian and specular surface reflectance characteristics (BRDF) affect satellite measurements at nadir only insignificantly but can make large differences for off-nadir observations.

The details of these results are also published and led us to our most recent investigations of how typical non-Lambertian angular canopy reflectance characteristics may be used for scene identification.

Identifiers for horizontally homogeneous vegetated surfaces that may be used in remote sensing are the spectral distribution and the angular distribution of radiances above the canopy. The spectral distribution is determined by the optical properties of the constituents of the particular canopy, e.g., leaves and stems, while the angular distribution is created mainly by the canopy architecture. While the spectral characteristics of most canopy components are very similar for most plants, the canopy architecture may be most dissimilar. This fact leads to intrinsic canopy angular reflectance patterns that may be typical for certain classes of plant canopies. Thus, the atmospheric perturbations of the angular reflectance pattern of a Lambertian, a mixed Lambertian/specular surface, and of the measured BRDFs of savannah and coniferous forest canopies were studied using aerosol-free and polluted atmospheres.

Two typical results of our calculations are shown in Figs. 1 and 2, where measured angular reflectance patterns above real canopies are computationally "transported" through a mildly aerosol-loaded atmosphere to a hypothetical off-nadir satellite sensor. These results show that maxima, like the canopy "hot spot" (a dominant peak when viewing in the direction of the sun with the sun at observer's back), are still detectable above the atmosphere even if observed through heavily aerosol-loaded atmospheres. It appears that especially those patterns that vary with the azimuth angle are better preserved than variations with view zenith angles. Note, in particular, how the shape of the reflectance pattern along the 180° azimuth changes when transported through the atmosphere, while variations with the azimuth along the 30° zenith remains basically the same. The underlying cause for this effect is obviously the constant path length through the atmosphere for all directions with the same view zenith angle. Thus, strong azimuthal variations typical for any surface or canopy reflectance pattern undergo only minor perturbations by the atmosphere, while the angular patterns for varying view zenith angles are much more perturbed by atmospheric effects. This finding suggests that off-nadir satellite observations with varying view azimuth angles may contribute significant new data that is expected to be valuable for crop identification.

In our search for an effective new atmospheric correction algorithm, we are presently performing exploratory calculations with the objective of reconstructing, from radiance distributions above the atmosphere, a typical angular reflectance pattern as measured directly above a canopy. Figs. 1 and 2 demonstrate clearly the severe atmospheric perturbations that are cumulatively added to the upwelling radiance distributions, especially in the visible wavelength region and for large view zenith angles. However, we show in Fig. 3 the result of a simple correction algorithm applied to the coniferous forest data (see also Fig. 1) for an aerosol-polluted, rural atmosphere of horizontal visual range of 23 km, equivalent to vertical optical depth at 0.55 μm of 0.45

for the entire atmosphere. The top half of the iso-radiance contour plots give Kriebel's measured data directly above the forest canopy while the bottom half shows our reconstructed radiance distributions from values above the atmosphere but corrected for atmospheric perturbations. This correction is based on a simple subtraction of the atmospheric path radiance component as determined from an independent additional radiative transfer calculation assuming purely Lambertian surface reflectance but with the same albedo as that of the real canopy. For our forest canopy, we have $\alpha = 11\%$ at $0.85 \mu\text{m}$. The comparison in Fig. 3 shows an agreement within approximately 10% between the measured and reconstructed radiance distributions for view zenith angles lower than 60° and all view azimuth angles. The hot spot is almost perfectly retrieved after this simple atmospheric correction. These results are both surprising and encouraging, because the correction apparently works very well even at the visible wavelength where atmospheric effects dominate the canopy signal by far.

The next logical step in our research project must be a two-pronged approach. First, the analysis of our (as yet) simple atmospheric correction algorithm must be broadened and studied in depth. Secondly, our physical understanding of how certain typical canopy reflection patterns are correlated with measurable biophysical canopy parameters must also be deepened. To achieve this latter goal, we propose to build a simulated vegetative canopy structure using only artificial (non-living) structure elements for leaves, stalks, branches, etc., that provides a well-defined and fully reproducible testbed for verification and testing of instruments and theoretical models in remote sensing. Since every natural vegetation canopy changes through growth, and its canopy components and architecture are intrinsically variable, reproducibility is seriously limited and measurements of biophysical parameters, such as leaf area index and leaf angle distributions, are prone to large uncertainties. In contrast, the artificial canopy provides a facility for "ground truth" measurements, testing and calibration of instruments, verification, and sensitivity testing of theoretical models as well as specific instruments. A synopsis of this proposal is attached.

If our preliminary findings about the invariance of typical local extremes in surface reflectance patterns to atmospheric perturbations can be further substantiated, then important conclusions should be drawn for the operation of future earth observing satellites. This result leads to the recommendation that off-nadir satellite observations in the near-infrared may contribute additional valuable information to crop identification as well as other scene identification when enough non-Lambertian (e.g. specular) reflectance is present. For crop identification it might be sufficient to swing an MSS or TM type scanner into the downward sun direction to observe the hot spot, and then rotate the instrument around a 360° azimuth for the constant solar zenith angle.

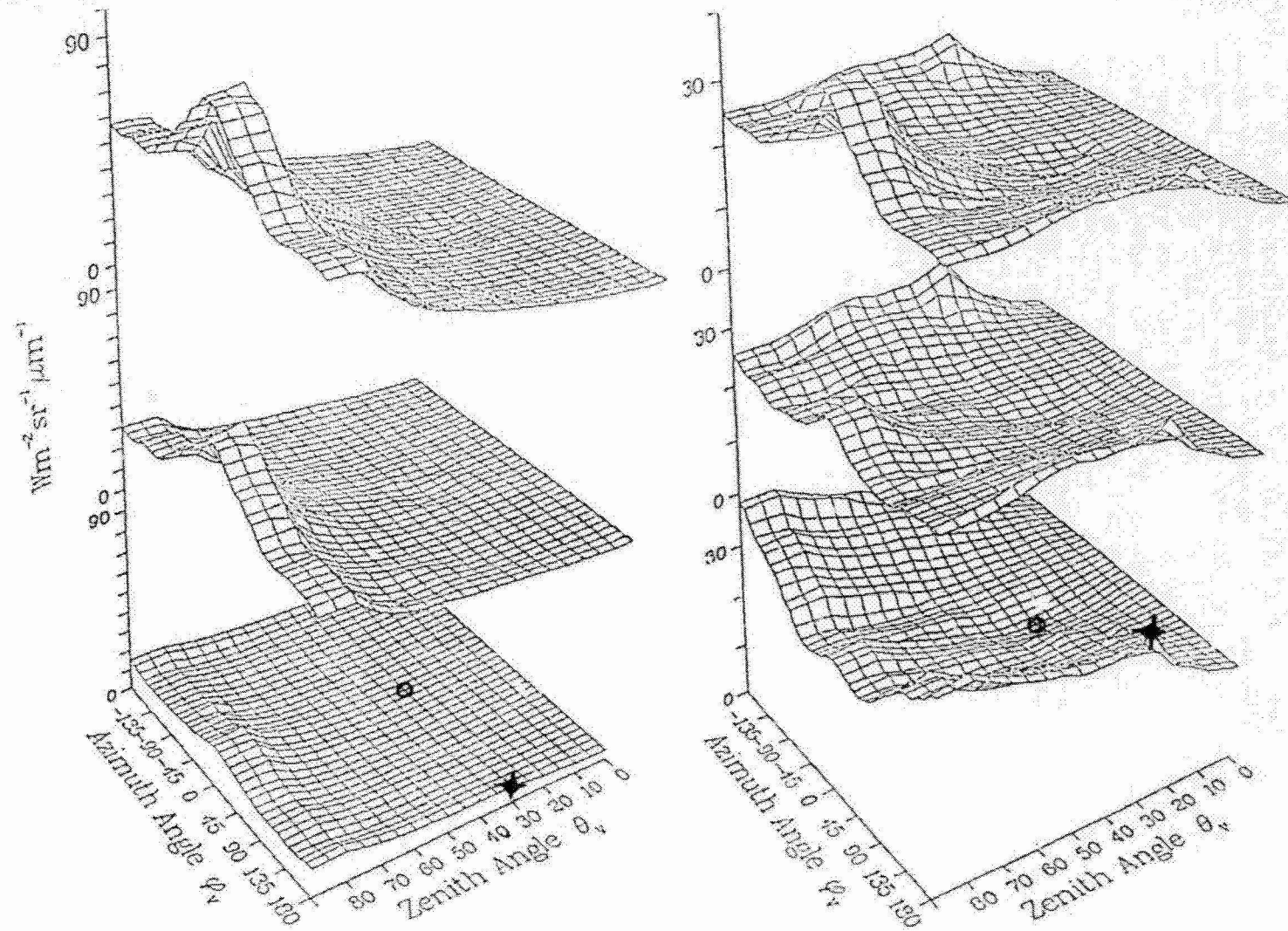
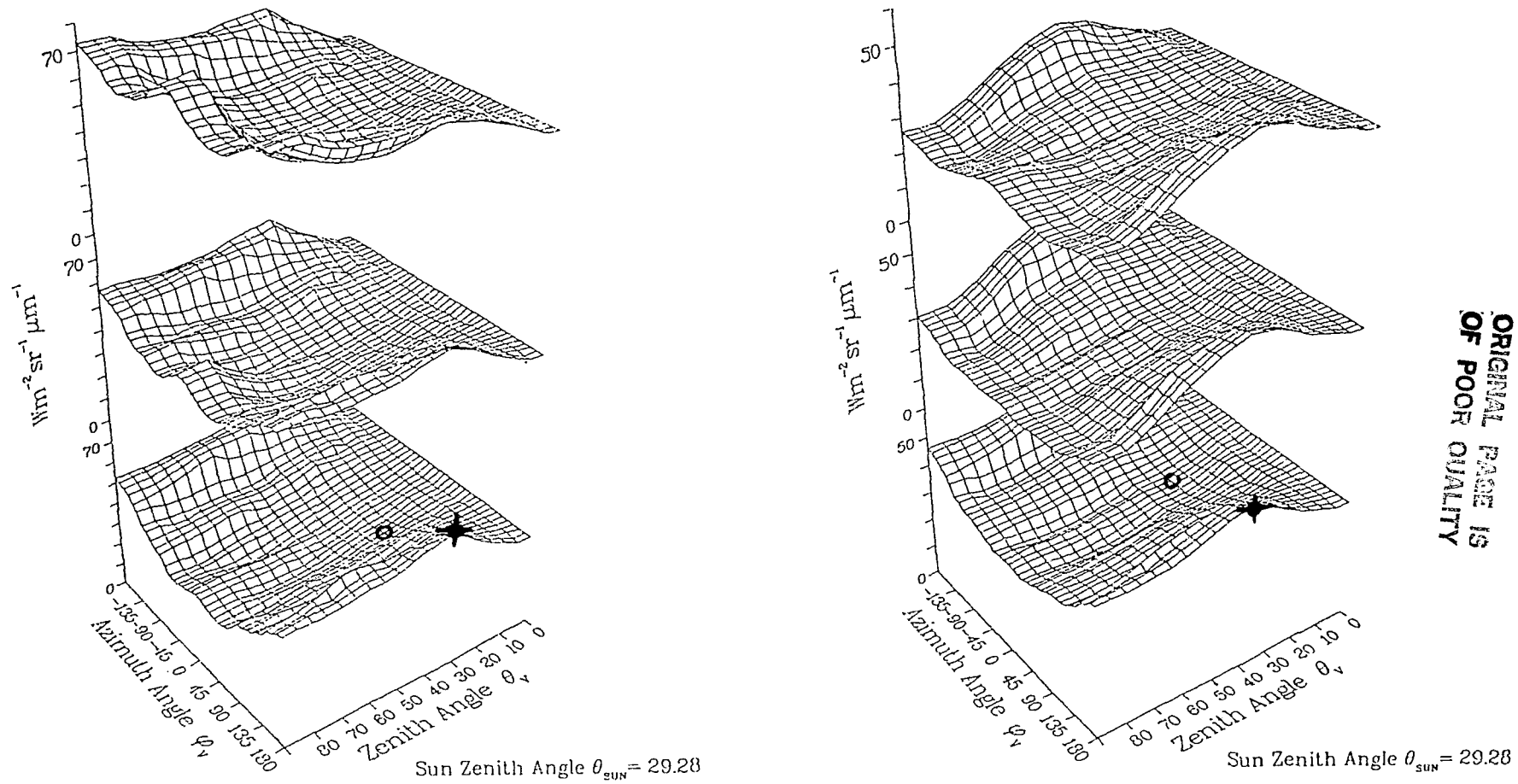


Figure 1. Los Alamos Calculations, November 1984, Coniferous Forest: Bottom boundary condition is measured Bidirectional Reflectance Distribution Function (BRDF) of coniferous forest by Kriebel (1977). Atmospheric model: Mid-latitude summer, rural boundary layer aerosol with visual range $V_0 = 23$ km, total optical depth of atmosphere $\tau = 0.45$. Surfaces refer to 0.0, 1.0, and 70 km from bottom to top. Surfaces show the up-welling radiance distribution at 0.65 (left) and 0.85 μm (right) for solar zenith angle 29.3° . Sundirection and direction opposite to sun are indicated by \star ("hot spot") and \circ , respectively.



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Figure 2. Los Alamos Calculations, November 1984, Savannah: Bottom boundary condition is measured Bidirectional Reflectance Distribution Function (BRDF) of Savannah by Kriebel (1977). Atmospheric model: Mid-latitude summer, rural boundary layer aerosol with visual range $V_0 = 50$ km, total optical depth of atmosphere $\tau = 0.25$. Surfaces refer to 0.0, 1.0, and 70 km from bottom to top. Surfaces show the up-welling radiance distribution at 0.65 (left) and 0.85 μm (right) for solar zenith angle 29.3° . Sun direction and direction opposite to sun are indicated by \star ("hot spot") and \circ , respectively.

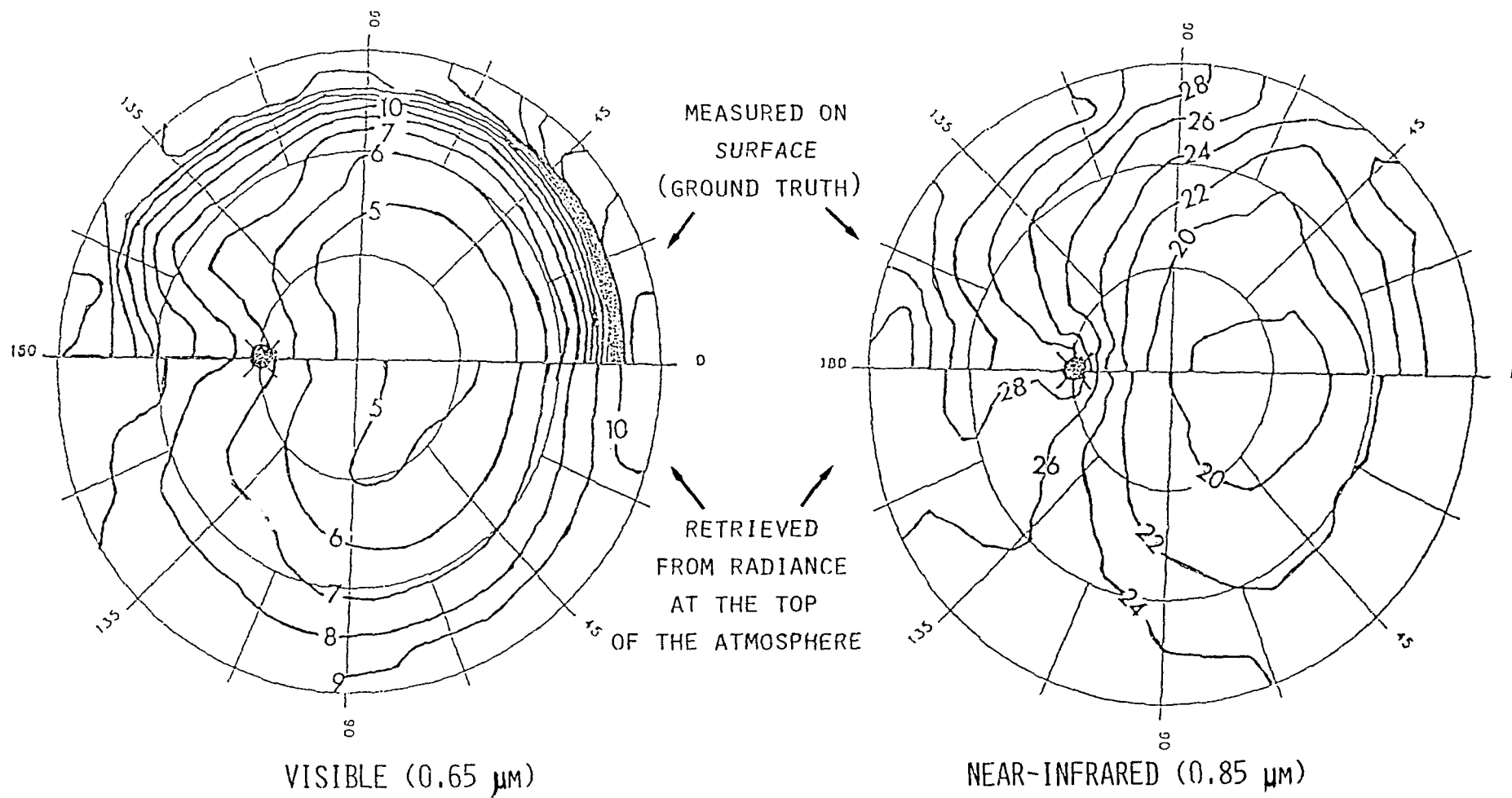


Figure 3. Upwelling radiance distribution of coniferous forest at surface (upper half) compared with radiance at top of the atmosphere, corrected for the atmospheric perturbation (lower half). $V_0 = 23 \text{ km}$.