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UNDERSTANDING THE RADIANT SCATTERING BEHAVIOR OF VEGETATED SCENES

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Fundamental knowledge of the physics of the scattering behavior of vegetation as gained in this study is important. This growing body of knowledge will ultimately serve the remote sensing and earth science community in many ways. For example, it will provide (1) insight and guidance in developing new extraction techniques of canopy characteristics, (2) a basis for better interpretation of off-nadir satellite and aircraft data, (3) a basis for defining specifications of future earth observing sensor systems, and (4) a basis for defining important aspects of physical and biological processes of the plant system. Such fundamental knowledge is very important to the long term advancement of remote sensing and earth science programs. The overall objective of the three-year study is to improve our fundamental understanding of the dynamics of directional scattering properties of vegetation canopies through analysis of field data and model simulation data. The specific objectives were to (1) collect directional reflectance data covering the entire exitance hemisphere for several common vegetation canopies with various geometric structure (both homogeneous and row crop structures), (2) develop a scene radiation model with a general mathematical framework which will treat 3-D variability in heterogeneous scenes and account for 3-D radiant interactions within the scene, (3) conduct validations of the model on collected data sets, and (4) test and expand proposed physical scattering mechanisms involved in reflectance distribution dynamics by analzying both field and modeling data.

Using a Mark III 3-band radiometer, directional reflectance distributions spanning the entire exitance hemisphere were measured of natural vegetation canopies ranging from bare soils to complete with 100% ground cover. NOAA 7/8 AVHRR bands 1 (0.58-0.68 μm) and 2 (0.73-1.1 μm) were used in data collection. The cover types reported were corn, soybeans, grass lawn, orchard grass, alfalfa, cotton row crops, pine forests, hardwood forests, plowed fields, annual grassland, steppe grassland, hard wheat, salt plain, and irrigated wheat. All measurements were taken from the ground except the forest canopy measurements which were taken from a helicopter. Leaf area index, leaf angle orientation distributions, probability of gap functions, leaf reflectance and transmittance, and soil reflectance were measured on some of the canopies.

A three-dimensional radiative transfer model was developed (Fig. 1) and is unique in that it predicts (1) the directional spectral reflectance factors as a function of the sensor's azimuth and zenith angles and the sensor's position above the canopy, (2) the spectral absorption as a function of location within the scene, and (3) the directional spectral radiance as a function of the sensor's location within the scene. It is one of two existing models with such general three-dimensional capabilities. This 3-D model was expanded to include the anisotropic scattering properties of leaves as a function of the leaf orientation distribution in both the zenith and azimuth angle modes. The model was applied to complete vegetation canopies of various leaf orientations--erectrophile (mostly erect leaves), planophile (mostly horizontal leaves), spherical (equal probability of all leaf orientations), and heliotropic (sun tracking leaves). The model was also validated and analyzed for agricultural crop canopies, natural grassland canopies and forest canopies. The model was used to explore the radiative transfers that take place in these various scenes.

The analysis of the field data and model simulations yielded significant information on the radiant scattering behavior of the vegetation canopies. The results showed unique reflectance distributions ranging from bare soil to complete vegetation canopies for agricultural crops and natural grasslands. Physical mechanisms causing these trends were proposed based on scattering properties of soil and vegetation. Soil exhibited a strong backscattering peak toward the sun (Fig. 2). Complete vegetation exhibited a "bowl" distribution with the minimum reflectance near nadir (Fig. 3). Sparse vegetation canopies showed shifting of the minimum reflectance off of nadir in the forward scattering direction because both the scattering properties of the vegetation and soil were being observed. In addition, sparse canopies exhibited the strong backscatter peak of the soil at relatively small solar zenith angles. The largest variations in reflectance with changing view angle occurred at large solar zenith angles for canopies with very low vegetation covers. As vegetation densities increased and the solar zenith angle decreased, reflectance variations decreased. The dynamics of the directional reflectance distributions were analyzed and physical principles responsible for the observed dynamics were proposed. Past studies have demonstrated that the normalized difference transformation [AVHRR (Band 2 - Band 1)/(Band 1 + Band 2)] is useful in monitoring green vegetation biomass. A difficulty in utilizing AVHRR data that scans out to 56° is that the signal for any particular target can change significantly with various view angles. It was demonstrated that this transformation generally decreased the directional variation of the signal. However, there were exceptions. For each remote sensing application the user should be aware of these variations for the specific cover types being studied, solar zenith angle and scanning direction of the sensor with respect to the solar azimuth. It was found that complete canopies with different leaf orientation distributions (erectophile, spherical, planophile, and heliotropic) had unique reflectance distribution characteristics. The dynamics of these distributions were physically explained by directional scattering effects of two mechanisms. The first mechanism causes the characteristics "bowl" shape of complete canopies that is--increasing reflectance with increasing off-nadir view angle for azimuth directions. It is caused by shadowing gradients and view projection gradients within the canopy. The second mechanism is the primary directional scattering of the leaves (phase function) due to leaf orientation, source direction, and leaf transmittance and reflectance values. The combination of these two mechanisms in the various canopies are responsible for the dynamics of the overall shape of the directional reflectance distributions.

The results showed that the scattering behavior of relatively dense forest canopies is very similar to the scattering behavior of agricultural crops and natural grasslands. Only in more sparse forest canopies with significant spacing between the tree crowns (or clumps of tree crowns) does the scattering behavior deviate from homogeneous agricultural and natural grassland canopies. This clumping of vegetation material has two effects on the radiant transfers within the canopy. (A) It increases the probability of gap to the understory and/or soil layers which increases the influence of the scattering properties of these lower layers and (B) It increases dark shadows within the scene causing increased backscatter and decreased forward scatter to occur relative to the homogeneous case. Both phenomenon tend to increase backscatter relative to forward scatter. For typical forest canopies, the peak backscatter reflectance can be increased as much as 30% relative to an equivalent homogeneous canopy due to phenomenon A and 35% due to phenomenon B. The combined effect of phenomenon A and B can cause typical increases of 65% or higher. It is hypothesized that these phenomenon are especially important in sparse conifer forests such as the boreal forest which account for 50% of the world's forest area.

The understanding of the radiant scattering behavior of vegetated scenes gained in this studied can lead to intelligent techniques for extracting canopy parameters from remotely sensed data. For example, estimating the hemispherical reflectance (albedo) of terrestrial surfaces is of great importance in studying biospheric and atmospheric processes. It is proposed that satellite borne instruments represent the only practical means of obtaining global estimates of surface albedo data at reasonable time resolution; the problem being how to relate the nadir or directional reflectance observations from such sensors to the integrated hemispherical reflectance. This study investigated (1) the relationships between directional reflectances and hemispherical reflectance and (2) the effect of solar zenith angle and cover type on these relationships. The results showed that errors in inferring hemispherical reflectance from nadir reflectance can be as high as 45% for all cover types and solar zenith angles. By choosing a solar zenith angle between 30°-40° the same error is reduced to less than 20% in both bands. For both bands a view angle of 60° off-nadir and ±90° from the solar azimuth reduces this error to less than 11% for all sun angles and cover types. A technique using two specific view angles reduces this error to less than 6% for both bands and for all sun angles and cover types. These techniques may yield considerable dividends in terms of more reliable estimation of hemispherical reflectance of natural surfaces.

These fundamental research efforts have improved our physical understanding of radiant scattering in vegetation canopies. This has been accomplished through the analysis of both model simulation data and field directional reflectance data in the visible and near infrared wavelengths. The directional scattering behavior of vegetation has been described and explained for various solar zenith angles, and various canopies with different densities, leaf orientation distributions, and optical properties. The work has been in response to providing an intelligent basis for defining specifications of earth observing sensor systems and for inferring important aspects of physical and biological processes of the plant system.

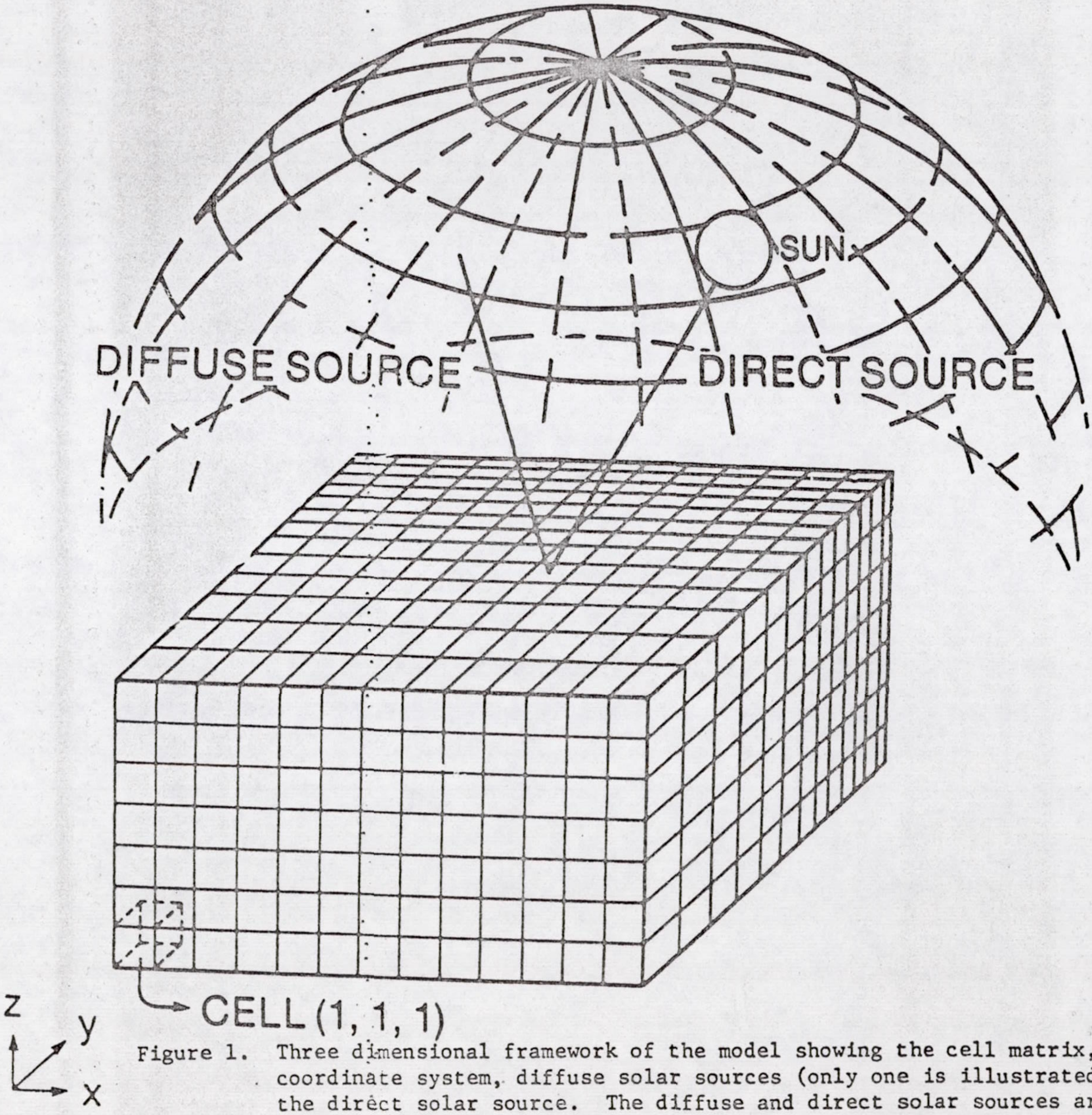

Figure 1. Three dimensional framework of the model showing the cell matrix, cell coordinate system, diffuse solar sources (only one is illustrated), and the direct solar source. The diffuse and direct solar sources are extended down to the surface of each cell on the top surface of the cell matrix. Any 3-D scene can be represented by "filling" the cells with various materials with different densities and scattering properties.

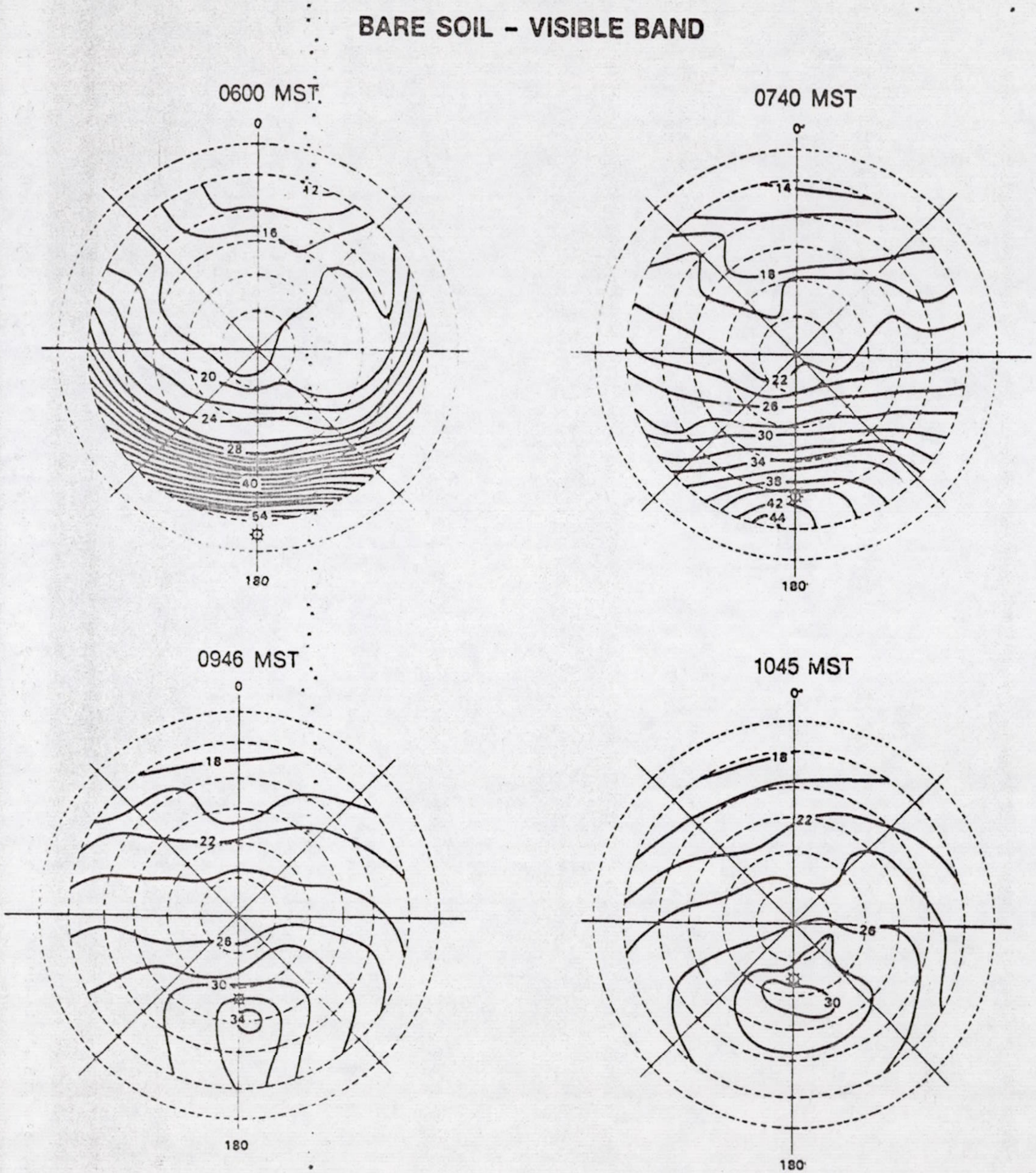

Figure 2. Polar plots of isolines of percent directional reflectance in the visible band for bare soil. The distance from the origin represents the off-nadir view angle of the sensor and the azimuth angle represents the sensor's azimuth. The solar azimuth is always 180°. A sensor with 0° azimuth looks into the sun, the dashed lines represent 15° increments of off-nadir view angle (0°-90°). The solar position is shown as a small starred circle on each plot.

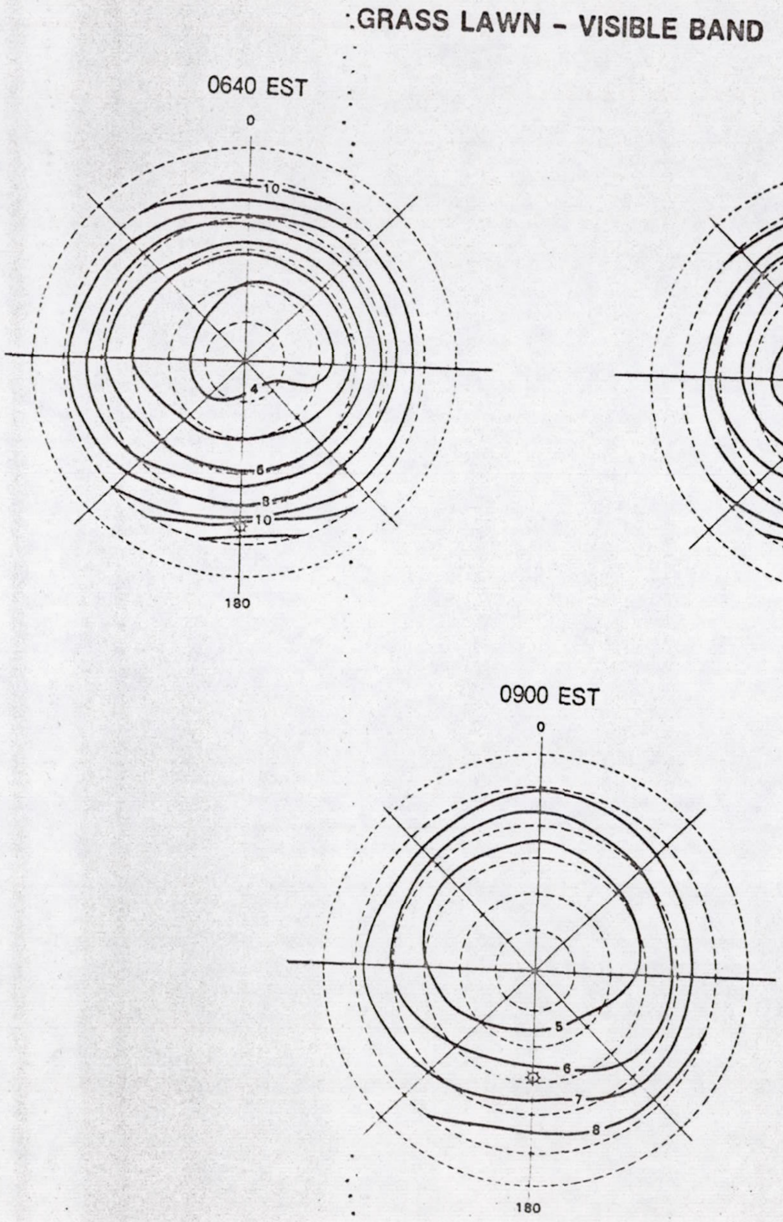

Figure 3. Polar plots of isolines of percent directional reflectance in the visible band for a grass lawn. Symbols follow Figure 2.