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ATMOSPHERIC CORRECTION OF REMOTELY SENSED SPACECRAFT DATA

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Abstract

A model designed to predict the transfer of radiative energy in the earth atmosphere is described. The computational procedure accounts for absorption and scattering processes at visible and near infrared wavelengths. This paper reports on application of the atmospheric model to the interpretation of ERTS Multispectral Scanner (MSS) data. Spectrally-averaged values of the radiance emerging at the top of the atmosphere are computed for each MSS Band.

It is concluded that ERTS MSS Band 4 data are to a high degree influenced by the water vapor content of the atmosphere. Knowledge of the meteorological conditions at the time of an ERTS overpass appears to be necessary in order to achieve maximum classification accuracy. The impact of this conclusion upon the accuracy of identification of surface features will next be determined.

Introduction

The ultimate objective of the atmospheric modelling studies conducted at Purdue University's Laboratory for Applications of Remote Sensing (LARS) has been to develop algorithms which improve the capability to remotely identify earth surface features by accounting for the presence of the atmosphere. Through two processes, (1) scattering of radiation by the particles which comprise the atmosphere and (2) absorption and re-emission by certain of its gaseous components, the atmosphere contributes to the signal obtained by a remote sensing instrument. If one were to view as noise this addition to the data which would be obtained in the absence of an atmosphere, then the goal is to improve the signal-to-noise ratio with an appropriately designed analysis filter.

Method of Computation

A physical model was adopted as the tool with which the goal could be reached. Such a model had to possess the capability to account for a surface and atmosphere both of which can absorb and scatter radiative energy and which interact between themselves subject only to the conservation of energy. The change dI_λ in an intensity I_λ as it passes through a region characterized by an absorption coefficient $k_{\lambda a}$ and a scattering coefficient $k_{\lambda s}$ is produced by three terms: 1) the extinction (the sum of absorption and scattering) of energy from the direction of propagation of I_λ from all possible incident directions, and 3) the emission of radiation from within the region into the direction of I_λ. Upon solving for the emergent radiance, two terms result: the first is the contribution of the original intensity reduced by extinction within the region, and the second is the additional radiance contributed by scattering and emission within the region itself.

Computation of intensities is made difficult particularly by the scattering process, since the intensities to be solved for appear in both differentiated and integrated forms within the same equation, properly called an integro-differential equation. Three techniques are available to solve the radiative transfer equation in a scattering atmosphere. The iterative technique (Herman and Browning, 1965) consists of repeatedly solving the transfer equation at all levels and for all directions desired until a consistent set of intensities is obtained. This would give the radiation field after one scattering process. Since multiple scatterings are possible these values then serve as input for a repeat of the iterative process for second order scattering. The computation is repeated for successively higher orders of scattering until sufficient accuracy is obtained, as dictated by energy conservation. In the Monte Carlo technique (Plass and Kattawar, 1968) very great numbers of individual incident beams of radiation are allowed to penetrate the scattering medium and to undergo the so-called "random-walk" to account for multiple scatterings. For sufficiently numerous repeats of this process a statistically smooth radiation field will result. In the Fourier series technique (Dave, 1970) it is possible to expand the scattering phase function for a particular direction of scattering in a series whose successive terms represent higher orders of scattering. Proper combination of many such series produces the desired scattered-radiation field.

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The Fourier series approach was selected and the required computational programs have been adapted to the LARS computer facility. Several physical parameters are important to the model. 1) Wavelength, λ: both the scattering and absorption processes are strongly wavelength dependent, a critical issue to any multispectral identification scheme. 2) Aerosol complex index of refraction, $m = n - ik$: the magnitude of scattered energy, given by n, and the relative amount of absorption, given by k, vary from one type of aerosol, a collection of relatively large particles of differing sizes, to another; for example, water and dust hazes have significantly different values of n and k in the visible and near-infrared portions of the spectrum. 3) Aerosol size distribution function, n(r) under various conditions the atmosphere can contain rather more or less particles of quite small or quite large sizes; the resultant scattering of radiation is sensitive to the relative and absolute abundances of each. 4) Aerosol height distribution function, n(z): meteorological conditions of wind and temperature determine whether particulate matter is confined near the surface or is distributed quite uniformally with height; the measured radiation at a given level in the atmosphere will be influenced by these differing conditions. 5) Gaseous absorption by H_2O, O_3, O_2, CO_2, etc: these several atmospheric gaseous components, some of which are quite variable with time can selectively deplete or augment the radiation in a given spectral interval, depending upon meteorological conditions. 6) Geometry, θ_o, ϕ_o, θ, ϕ: the relative location of the source of solar irradiance and of the direction of observation of emergent radiance can greatly influence measured values.

Values of radiance emergent in a given direction at a given level in the atmosphere are obtained through a series of computer programs named SPA, SPB, SPC, and SPD. The flow of information from one to another is indicated in Fig. 1.

SPA - computes coefficients of Legendre series for the scattering phase function of a spherical particle described by its size parameter $x = 2\pi r/\lambda$ and index of refraction $m = n - ik$.

SPB - computes coefficients of a Legendre series for the normalized scattering phase function of a unit volume (illuminated by an unpolarized, monochromatic and unidirectional beam of radiation) containing a known size distribution n(r) of spherical particles all made of the same refractive index $m = n - ik$.

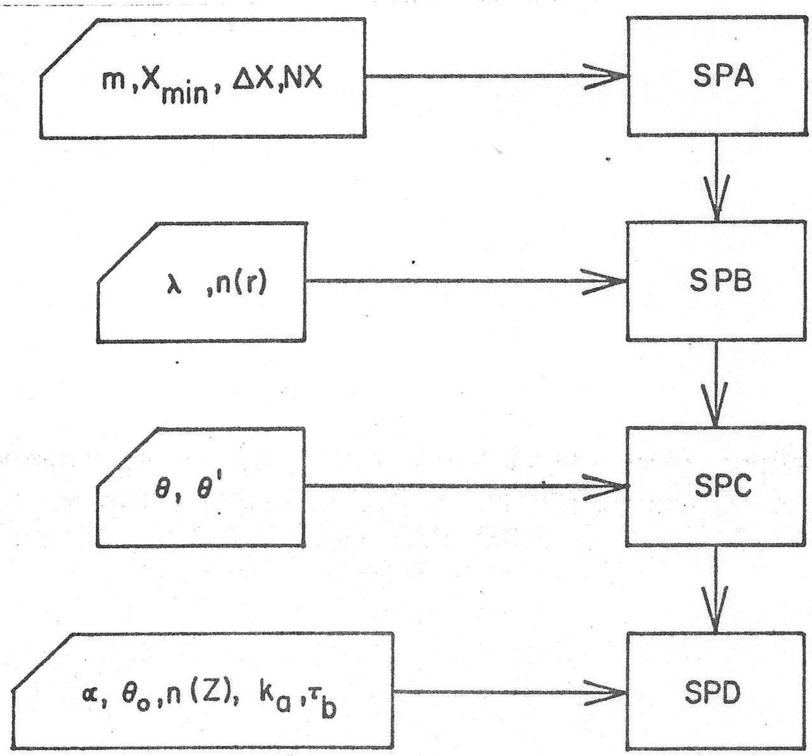

Fig. 1. Input parameters and flow of information between the several computing programs.

SPC - computes coefficients of a Fourier series for the normalized scattering phase function of a unit volume for radiation incident at a zenith angle Θ' and scattered at a zenith angle Θ. The argument of the Fourier series is $\phi' - \phi$, the difference between the azimuth angles of the incident and scattered beams of radiation.

SPD - computes the intensity of the scattered radiation emerging at selected levels of a plane-parallel, nonhomogeneous atmosphere containing an arbitrary vertical distribution of ozone and water vapor concentration and/or aerosol number density, and bounded at the lower end by a Lambert ground of known reflectivity.

One of the lengthy portions of the computational procedure entails summation of the contributions of various sized particles to the total scattered energy. The computer time involved directly depends on the choice of a size interval

$\Delta x = 2\pi\Delta/\lambda$. The accuracy of computed intensities also depends upon the resolution chosen for this numerical integration. Further, the computer time required depends upon the total size range considered, in particular upon the size of the largest particles included in the model; this is given in terms of r_{max}, the radius of the largest aerosol particles. Again, the resultant intensities are influenced by the contributions of these large particles. Values of intensity computed for three values of surface reflectivity are shown in Fig. 2. For this case, $\lambda = 0.55$ μm and $m = 1.50 - 0.03i$, representing a slightly absorbing aerosol. As a standard for comparison the aerosol size range extends over the 0.03 to 10 μm interval and has been integrated in steps of $\Delta x = 2\pi\Delta r/\lambda = 0.2$ over these limits. The values displayed are intensities of radiation observed along nadir as a function of solar zenith angle.

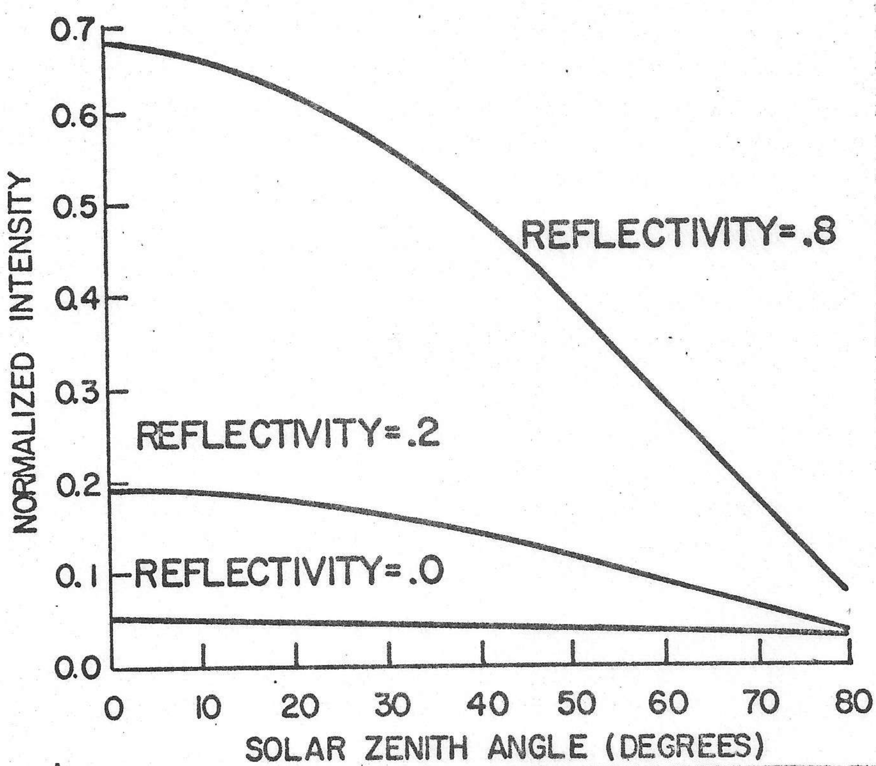

Fig. 2. Intensities observed along nadir at the top of the atmosphere as a function of solar zenith angle for $\lambda = 0.55$ μm and haze $m = 1.50 - 0.03i$.

The importance of surface reflectivity is apparent, since the contribution of the boundary irradiance is directly proportional to α. As the solar zenith angle increases and the effective atmospheric path increases, intensities decrease for all α, approaching zero at a solar zenith of 90^o.

Fig. 3 illustrates the importance of the parameters Δx and r_{max} to computed intensities; several sets of values have been selected and the computed intensities then compared to the values of Fig. 2 as percent departures from that standard case. The bottom curve for $\Delta x = 0.5$, $r_{max} = 10$ µm represents a less accurate integration over the selected aerosol particles size range. Errors of only a few tenths of one percent occur, these appear acceptable in view of the reduced computational time. If the coarseness of the integration increment is increased to $\Delta x = 1.0$, the errors introduced are much larger. When the presence of the larger particles between 2 and 10 µm radius is ignored the remaining two curves result.

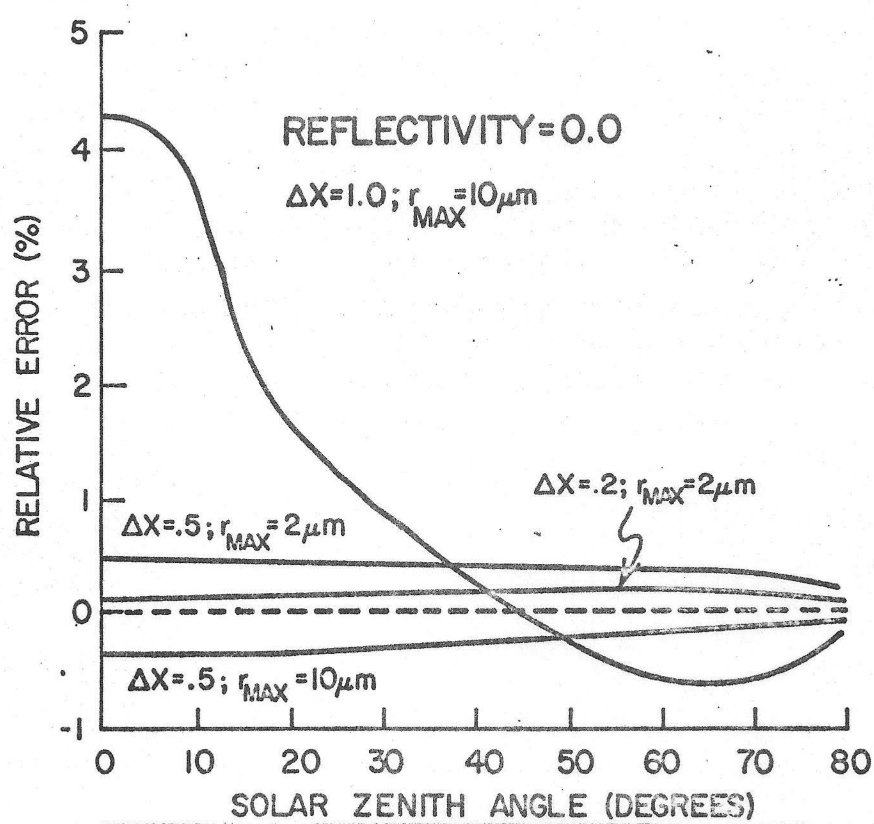

Fig. 3. The effect of computational parameters Δx and r_{max} on reflectivity = 0.0 curve of Fig. 2.

In neither case do the errors exceed a few tenths of one percent. As a consequence, it is concluded that the least time-consuming case for $\Delta x = 0.5$, $r_{max} = 2$ μm appears to give entirely acceptable results considering that the overall limitations of the model restrict accuracy to the order of 2 to 4%.

Values of the other required input parameters were needed before the physical model was ready for use. The absorption coefficient for ozone, K_{O_3}, the absorption coefficient for water vapor, K_{H_2O}, and the Rayleigh scattering optical thickness, τ_b are all wavelength dependent. Values of τ_b were presented as a function of wavelength by Elterman (1968). The variation of K_{O_3} is found in the Handbook of Geophysics (1960). Detailed research on the absorptive properties of water vapor in the portion of the spectrum in which the ERTS MSS is receptive, however, has only recently been conducted. Selby and McClatchey (1972) published a high-resolution study of water vapor absorption. In their atmospheric transmittance model, an absorption index for water vapor is presented every 5 cm^{-1}, and then is related to the equivalent absorption coefficient. The results of Selby and McClatchey were adopted for use in the physical model.

Since the model requires a single value of wavelength as input, spectrally averaged values for the absorption coefficient for ozone, $\bar{K}_{O_3}$, and water vapor, $\bar{K}_{H_2O}$, and Rayleigh scattering optical thickness, $\bar{\tau}_b$, must be derived. In direct correspondence with the averaging effect of the sensor's optical system on the signal produced in each band, the mean value of a parameter x can be obtained from the relation

$$\bar{x}_i = \frac{\int_0^\infty x(\lambda)\, E_i(\lambda)\, d\lambda}{\int_0^\infty E_i(\lambda)\, d\lambda} \qquad i = 1,2,3,4$$

where $E_i(\lambda)$ is the optical filter response of the i^{th} ERTS band. These computations were made using the average ERTS MSS filter response curves shown in Fig. 4. The results are tabulated in Table I.

Table I. Absorption Coefficients and Rayleigh Scattering Optical Thickness for ERTS MSS channels

ERTS Band	$\bar{K}_{O_3}$	K_{H_2O}	$\bar{\tau}_b$
1	0.0826	0.0	0.1028
2	0.0689	0.0	0.0514
3	0.0	0.0184	0.0298
4	0.0	0.1255	0.0147

To complete the required input parameter values, a size distribution function for the atmospheric particulate matter is necessary. A discontinuous power law function as advocated by Bullrich (1964) was decided upon. Its form is

$$n(r) = C \qquad r_{min} \leq r < r_m$$

$$n(r) = C\left[\frac{r_m}{r}\right]^4 \qquad r_m \leq r \leq r_{max}$$

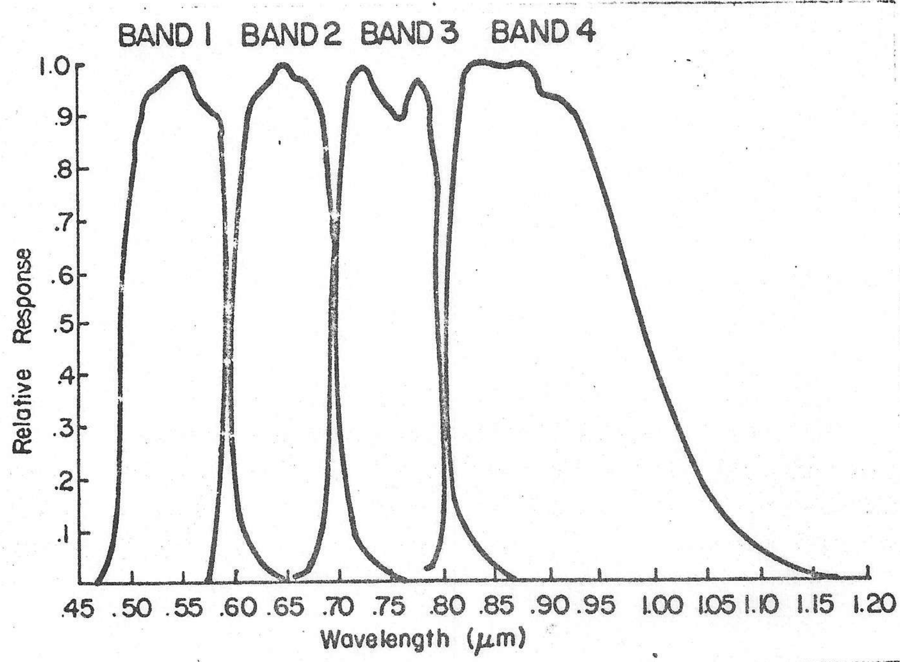

Fig. 4. Filter response curves for the four MSS channels of ERTS.

where n(r) is the number of particles per unit volume per one micron radius interval at radius r, r_{min} is the radius of the smallest particle included in the model, r_{max} is the largest permissible radius, and r_m is some intermediate value marking the transition from a constant value to the power law variation.

Results

By fixing the reflectivity of the surface in the model at a constant value, the effect of a change in the value of an atmospheric parameter can be studied. Because of its high variability and expected high degree of influence on the total transmittance of the atmosphere, water vapor content has been chosen as the parameter. Figure 5 illustrates the variation with the solar zenith angle at the top of the atmosphere of the upward-travelling radiance for each of the four ERTS MSS bands. The results of the atmosphere model are based on the vertical distribution and content of ozone, aerosol, and water vapor for an average midlatitude summer atmosphere. These input data were obtained from McClatchey et al. (1972). The driving force for the model is the solar flux density and the fixed surface reflectivity of 20%. The solar flux received by an ERTS MSS band was found by using the same averaging scheme

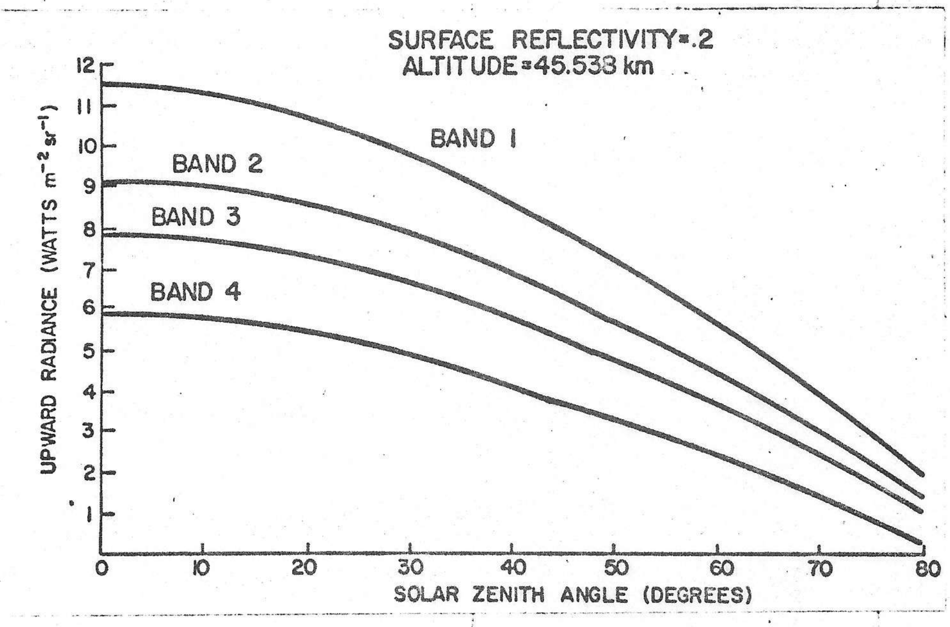

Fig. 5. Upward radiance at the top of the atmosphere for each ERTS MSS band versus solar zenith angle. Average midlatitude summer conditions apply.

that was used for the absorption coefficients and the Rayleigh scattering optical thickness. The wavelength dependent solar irradiance incident at the top of the atmosphere as found in the Handbook of Geophysics (1960) was averaged to yield the driving force for each MSS band. Since the solar flux is highest in the spectral interval of the first band, the upward radiance received by that band is higher than any of the other bands. Also, as the solar zenith angle increases, the upward radiance diminishes as expected because of the added path length through which the solar flux must pass.

The absorption spectrum of water vapor in the visible and near-infrared consists of weak bands located in the parts of the spectrum in which only MSS bands 3 and 4 are receptive. Thus, the radiances recorded by bands 1 and 2 are unchanged if the atmospheric water vapor content is altered and if all other things remain constant. Two additional cases of the atmospheric model have been run. In one, the water vapor content is decreased to one-half of the average midlatitude summer atmosphere amount, and in the other, the content is reduced to zero.

Fig. 6 displays the upward radiance reaching the MSS Band 3 sensor for the three cases of no water vapor, 1/2 the average amount, and the average midlatitude summer atmosphere

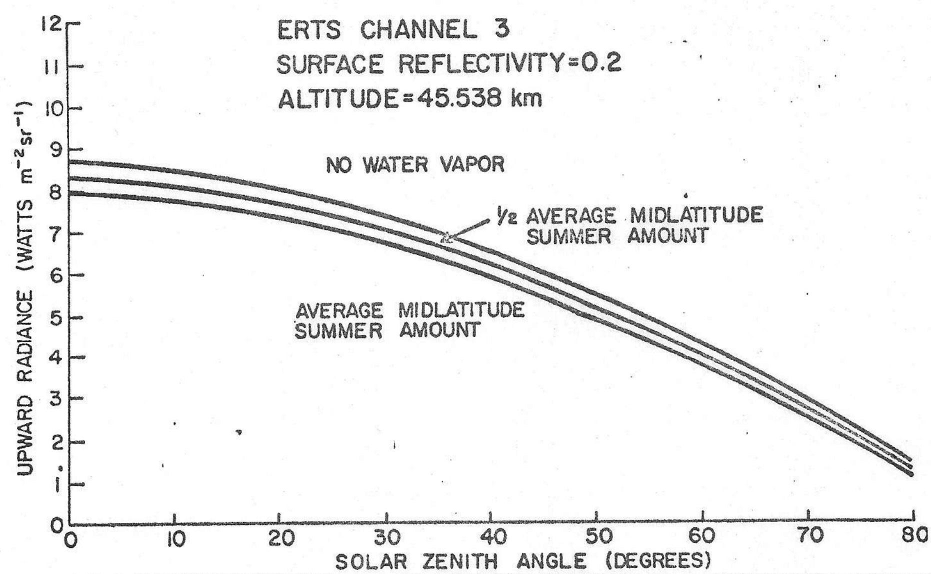

Fig. 6. Upward radiance at the top of the atmosphere for ERTS Channel 3 versus solar zenith angle for several values of total atmospheric water content.

amount. At a solar zenith angle of 0^o, there is only an 8.5% change in the value of the emerging radiance. Fig. 7 is a similar graph except for the MSS Band 4 sensor. For the case of the sun directly overhead, this time there is an 80.5% change in radiance.

Lee, Ogle, and DeKalb Counties in northern Illinois have been chosen as a case study to investigate the atmosphere's effect on emerging radiances. Meteorological data were gathered from the National Meteorological Center for the area at the time of the overpass on August 9, 1972. An upper-air sounding from Peoria and ground observations from Peoria, Rockford, and O'Hare Airport were all obtained, from which vertical distributions of ozone, water vapor, and aerosol concentration have been deduced. Based on climatological data for northern Illinois, a complex index of refraction of 1.33-0.0i, corresponding to a water-base aerosol, was selected. Land-use information and spectrophotometer data for the prominent surface crops in the three county area were found. By weighting the crop reflectance in a band with the percentage of land occupied by that crop in August, 1972, a spectral surface reflectivity has been computed. With the average absorption coefficients, the average Rayleigh scattering optical thickness, the surface reflectivities, and the vertical distributions, the atmospheric model has been run for each of the four ERTS bands. The results are tabulated in Table II.

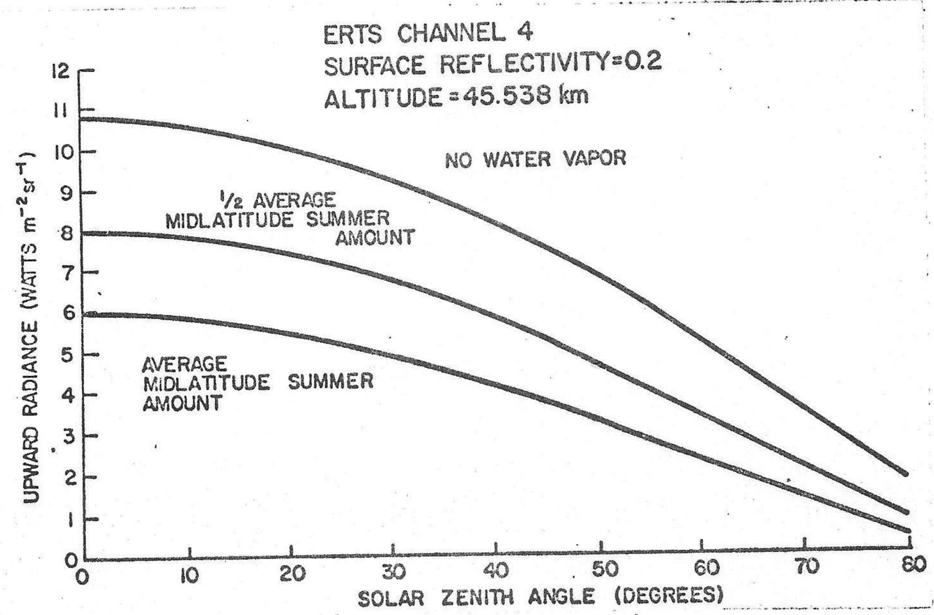

Fig. 7. Same as Fig. 6, except for ERTS Channel 4.

Table II. Northern Illinois Reflectivities and Atmospheric Transmissivities

ERTS Band	Surface REflectivity	Atmospheric Transmission (%)
1	0.1435	105.69
2	0.1096	89.38
3	0.4135	75.52
4	0.4718	61.90

In band 1, 105.7% of the radiant energy leaving the surface reached the sensor, while increasing amounts of energy are lost to the sensor as Bands 2, 3, and 4 are considered. Band 4 is the most strongly affected by the atmosphere, with only 61.9% of the radiative energy leaving the surface reaching the sensor.

Conclusions

It has been determined that the ERTS MSS Band 4 data are to a high degree influenced by the water vapor content of the atmosphere. Consideration of the meteorological conditions at the time of an ERTS overpass in this light appears to be essential for maximum classification accuracy to be achieved. With this information in hand, work is proceeding to determine what the impact actually is on the accuracy with which surface features can be identified.

Acknowledgements

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