Brent N. Holben
Christopher O. Justice
Earth Resources Branch
NASA/Goddard Space Flight Center
Greenbelt, MD 20771

The Topographic Effect on Spectral Response from Nadir-Pointing Sensors

A wide range of pixel values can be associated with one cover type due solely to variations in slope angle and aspect.

Abstract: *Since the inception of the Landsat earth resources satellite, a wealth of data on earth resources has become available. Applications for these data have been found in many disciplines, yet their usefulness in areas of rugged terrain is limited by the topographic effect on the sensor response. For enhanced application of these data in such areas, the topographic effect must be quantified. A field experiment, using a hand-held radiometer, was designed and conducted to assess a simple theoretical incidence model for simulating the topographic effect on a uniform sand surface.*

Seven data sets were taken to compare effects of solar elevation and azimuth encountered at different times of year. Analysis of these data showed considerable variation in radiance values for different slope angles and aspects and that these values varied considerably with changes in solar elevation and azimuth. The field measured variations in spectral response were found to have generally strong correlations (r > 0.95) with the theoretical model. The reasons for the occurrence of lower correlations are given and methods for improving the model are suggested.

A model to simulate Landsat sensor response was applied to two subsets of the field data to establish the magnitude of the topographic effect on satellite data. A range of 50 pixel values was obtained for the high solar elevation data subset, showing that a wide range of pixel values can be associated with one cover type due solely to variations in slope angle and aspect.

Introduction

In an effort to realize the potential of remotely sensed data for earth resources applications, research is being undertaken to increase our understanding of the spectral properties of natural surfaces and to examine the applications of such data to many parts of the world. Large areas of the Earth's surface are composed of rugged and mountainous terrain, areas which are often inaccessible and rich in natural resources. Existing environmental data bases for such areas are often poor. For effective regional planning and resource management, there is a need for accurate and up-to-date inventories of land cover and careful monitoring of resource exploitation. Remotely sensed satellite data have considerable potential for providing environmental information for such areas. However, recent studies have revealed problems, particular to the interpretation of multispectral data in areas of rugged and mountainous terrain, caused by the "topographic effect" on the sensor response (Cicone *et al.*, 1977; Fleming *et al.*, 1975; Hoffer and Staff, 1975; Justice, 1978; Miller *et al.*, 1978).

The topographic effect is caused by the differential spectral radiance due to surface slope angle

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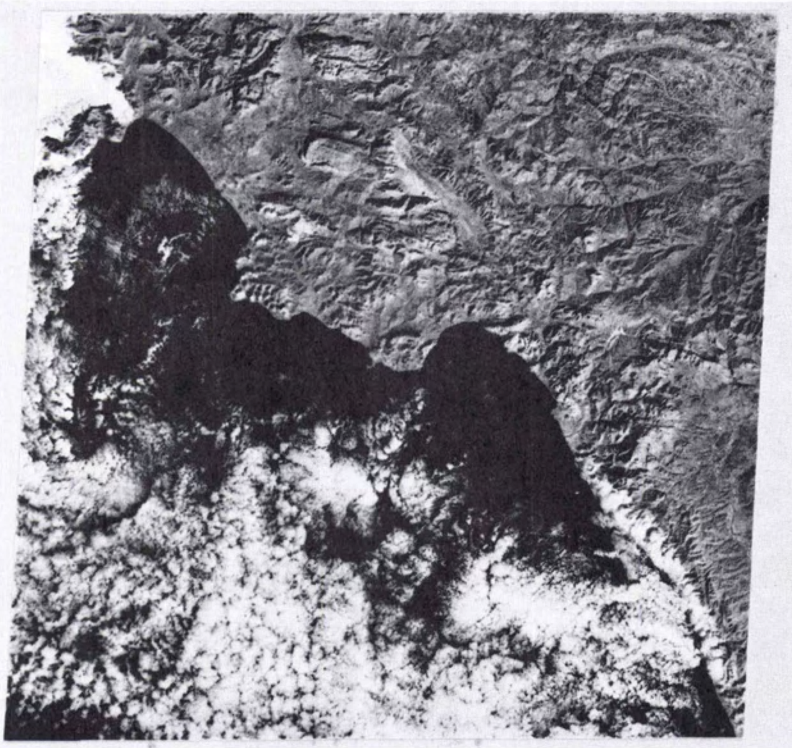

FIG. 1. Landsat, channel 5, 6 November 1972, sun elevation 30°.

and aspect variations and may be quantified by measuring the difference in radiance between a horizontal and sloping surface. The topographic effect is manifested on satellite images by visual impression of the relief of an area (Figure 1). Cover classification using multispectral data in mountainous areas is hampered because surfaces of the same cover type but with different slope angles and aspects have different radiance values (Sadowski and Malila, 1977). Multitemporal studies are also made difficult because the topographic effect appears to vary with solar elevation and azimuth. Comparison of the November image (Figure 1) with an August image (Figure 2) shows that the topographic effect changes with time of imaging and is more marked at the lower sun angle. If remotely sensed data are to be used effectively in areas of mountainous terrain, it is necessary to quantify, understand, and model the topographic effect.

The objective of the research presented in this paper was to examine and quantify topographic induced variations in spectral response from a uniform surface; to assess the suitability of a simple incidence model for modeling the radiance from the surface; and to simulate Landsat sensor response due to such topographic variations. To achieve these objectives, it was necessary to obtain radiometric measurements from a large range of slope angles and aspects for a simple uniform surface at a range of solar elevations. Obtaining such data from satellite sensors is impractical; therefore, a field experiment was designed to collect spectral data using a hand-held radiometer.

The solar radiation received at a surface is termed incident solar radiation and is composed of direct and diffuse radiation. Under clear skies, the diffuse component will be a small proportion of the incident radiation. The radiation reflected from a surface is termed radiance and is a function of the optical properties of the surface; the angle between the normal to the surface and the light source, i.e., the angle of incidence; and the angle between the normal to the surface and the sensor, i.e., the angle of exitance (Figure 3). If the surface is Lambertian, i.e., the measured radiance does not vary with view angle (Reeves, 1975), then the direct radiance is simply a function of the incidence angle. Several studies which have attempted to correct for sun angle variations have used the Lambertian model (e.g., Rouse *et al.*, 1973; Deering *et al.*, 1975; Cicone *et al.*, 1977) One of the objectives of this study was to assess the suitability of the Lambertian model for simulating the measured radiances. The following sections of this paper describe the theoretical model, the field data collection technique, the field measurements, and the statistical correlation between the field

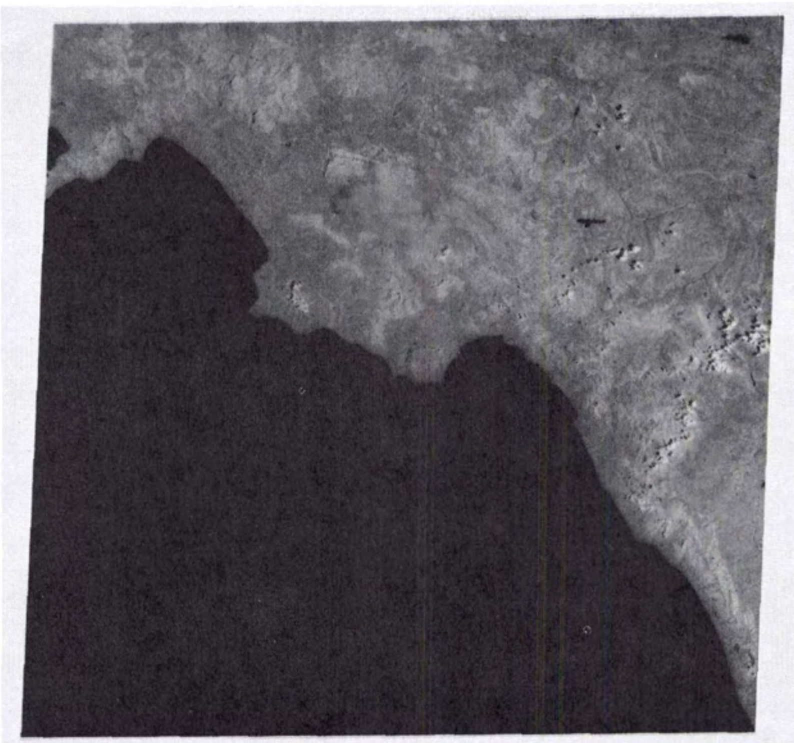

FIG. 2. Landsat, channel 5, 8 August 1972, sun elevation 55°.

data and the theoretical data with reference to the topographic effect and the simulation of the Landsat sensor response to the field data.

THE LAMBERTIAN MODEL

Under conditions of a constant atmosphere at a point in time, the irradiance impinging inclined surfaces of different slopes and aspects is a function of the angle of incidence. The incidence angle is the zenith angle for inclined surfaces (Z') and is the angle between the normal to the inclined surface and the solar beam (Figure 3). Z' may be calculated by (Robinson, 1966)

$$\cos Z' = \cos E \cos Z + \sin E \sin Z \cos A_z$$

where

E = slope inclination (angle of exitance),
Z = solar zenith angle, and
A_z = difference between the sun's azimuth and the slope aspect ≡ azpect.

Z' applies specifically for the incidence angles for direct solar radiation and is therefore a function of the surface slope, the solar elevation, and the angle between the sun's azimuth and the slope aspect. The latter variable will be referred to within this text as the azpect. The azpect, A_z, is the orientation of the slope measured clockwise from solar azimuth (Figure 3). Values for Z' can be calculated to show the range of incidence values from a series of slope angle-aspect configurations relative to a horizontal surface. By calculating angle of

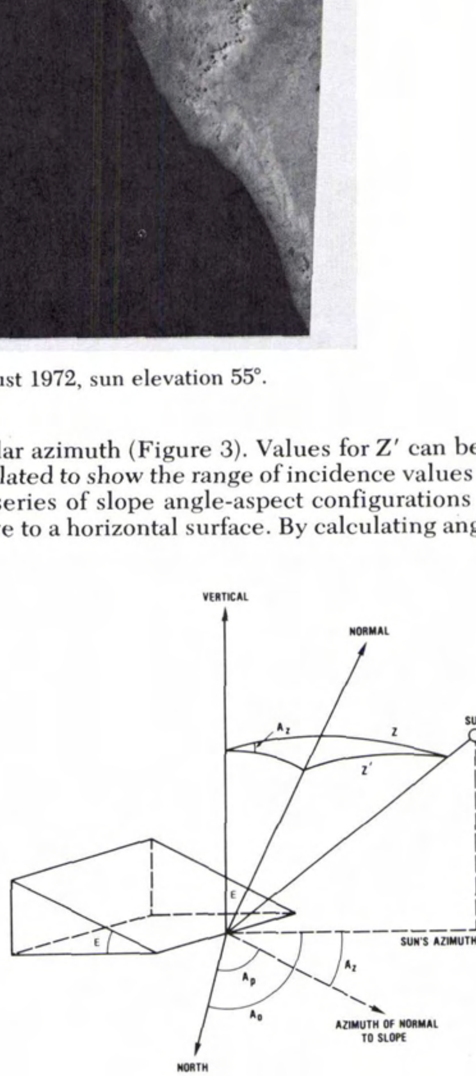

FIG. 3. Diagram showing the zenith angle, Z, incidence angle, Z', surface slope angle = angle of exitance, E, solar azimuth, A_0, aspect of the surface, A_p, and azpect of the surface, A_z, which are inputs to the theoretical incidence model (after Sellers, 1965).

incidence values for 21 December and 21 June at 9:30 A.M. mean solar time (MST) for a given latitude, we can obtain some indication of the variation of incident radiation affecting the Landsat sensor response during a yearly cycle (Figure 4). By this method we can also determine the slope angle-aspect configurations that are likely to be in shadow at different times of year (i.e., with different solar elevations and azimuths).

Cicone *et al.*, (1977), Tom and Miller (1977), and Justice (1978) included solar incidence values in Landsat studies. These authors examined correlations between incidence values and Landsat radiance data and concluded that incidence values could aid in the discrimination of cover types. Correlation coefficients were found to vary with cover type, e.g., from 0.45 for lodgepole pine to 0.17 for spruce fir (Cicone *et al.*, 1977). The relationship between the incidence model and spectral data for different cover types is unclear and, before applying the incidence model to satellite data, there is a need to examine further the relationship between the direct light incidence model and multispectral sensor response.

Field Testing of the Theoretical Incidence Model

Spectroradiometric measurements of a uniform sand surface, tilted at different angles and aspects at different solar elevations, were taken to quantify the topographic effect. A natural non-vegetated surface was chosen in order to minimize complexity of directional scattering. Seven radiance data sets were collected from 5 June 1978 to 26 September 1978 at various times of day. Uncalibrated radiances were collected using a two channel hand-held radiometer with bands in the red (0.65-0.70 μm) and photographic infrared (0.775-0.825 μm) (Pearson *et al.*, 1976; Tucker, 1978). The sensors were nadir-looking at a uniform sand surface inclined from 0 to 70 degrees in 10 degree increments. Four radiance measurements were taken at seven slope intervals for each azpect. This series of measurements, which took five minutes, was repeated at 22.5 degree intervals from the instantaneous solar azimuth. The radiance measurements taken at the slope intervals for each azpect were termed "azpect strings." Measurements were taken under cloudless skies and clear atmospheres, thereby assuring a minimal change of solar beam intensity during a monitoring session. Reference readings were taken from a horizontal barium sulphate plate and the horizontal surface before and after each azpect string. The four radiance observations for each slope angle were averaged and plotted as in Figure 5. The averaged field radiances for each slope were plotted relative to their associated horizontal surface radiance, thereby overcoming variations in irradiance during the measurement period. The topographic effect is quantified by differences between radiances and, therefore, does not necessitate the use of absolute values.

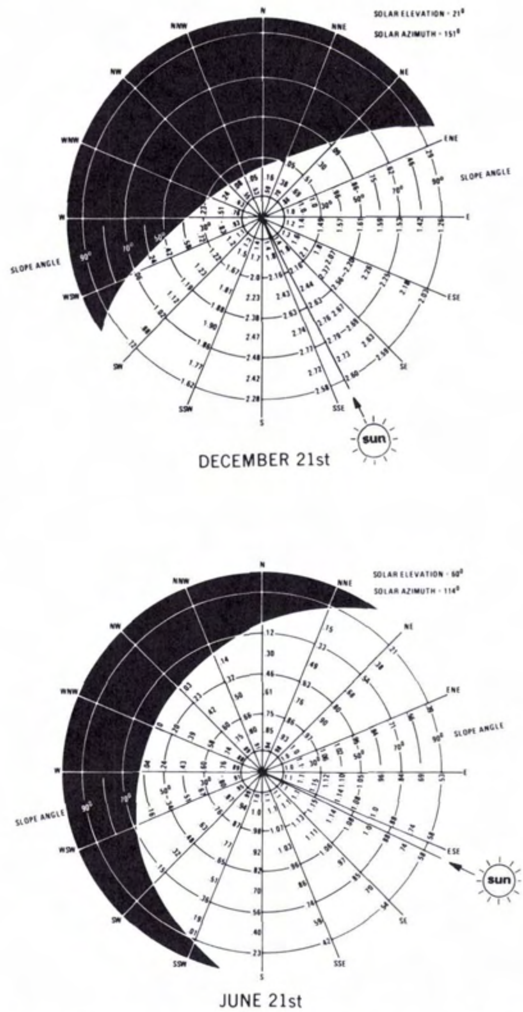

FIG. 4. Diagrams illustrating the range of relative theoretical direct incidence values encountered on 21 December and 21 June at 0930 mean solar time (for N40°).

Description of the Field Data

Variation of Radiance with Slope Angle and Azpect

The following description refers to an example of the red radiance (25 September, Figure 5), although the characteristics described are common to all the data sets. The radiance varied substantially with slope angle and azpect. The relative radiance values for the azpect strings 0°-180° were mirrored in the 180°-360° azpect strings. A smooth line connecting each point in an azpect string indicates a gradation of radiances. The greatest range of radiance values were found for azpects of

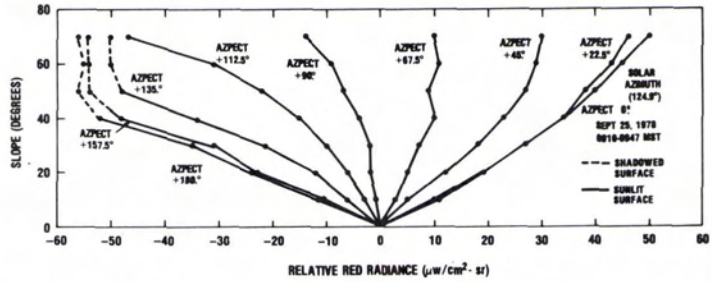

FIG. 5. Relative red radiance field measurements for a solar elevation = 40°.

0°-180° (i.e., slopes oriented in the principal plane). For the particular data set shown (Figure 5), the percentage change in radiance relative to the horizontal surface radiance was calculated for selected azpect strings.

The percentage change values for each azpect are presented in Table 1, and show that, for the time and date in question, the greatest deviation from the horizontal surface occurred for slopes oriented in the principal plane (azpect of 0° and 180°) and the minimum variation occurred for slopes approximately perpendicular to the principal plane (azpects between 67.5° and 90°). Radiometric variations with slope within shadowed azpect strings were very small.

COMPARISON OF VARIATIONS IN RADIANCE WITH SLOPE ANGLE AND AZPECT IN TWO SPECTRAL BANDS (0.65-0.70 μm AND 0.775-0.825 μm)

The plot for the photographic infrared band for 25 September is presented in Figure 6 for direct comparisons with the plot for the red band (Figure 5). The plots have similar shapes, which indicated that the sensor response to slope angle and azpect in the two channels is similar. Statistical correlation analysis was undertaken to correlate the red and photographic infrared measurements for the data sets. Pearsons Product Moment Correlation Coefficients, r, of greater than 0.95 were computed for all azpect strings. All correlations were significant at the 1 percent level. Radiance readings were lower for the photographic infrared band, and the percentage change in radiance was predominantly higher than for the red band, but this was due to the spectral reflectance properties of the sand surface. Although the two channels examined in the study respond similarly to slope angle-azpect variations, no assumption can be made at this stage concerning the response in other reflective bands.

TABLE 1. PERCENTAGE CHANGE IN RADIANCE RELATIVE TO THE HORIZONTAL FOR SLOPE ANGLES AT SELECTED AZPECTS, 25 SEPTEMBER 1978, SOLAR ELEVATION = 40°.

Slope (in degrees)	Azpect (in degrees)				
	0	45	90	135	180
0					
10	17.7	7.6	1.5	9.1	15.5
20	30.6	18.4	3.0	18.2	33.8
30	43.5	27.6	3.0	31.8	45.4
40	54.8	35.4	6.1	51.5	73.2
50	64.5	41.5	10.6	72.7	78.7
60	72.5	44.6	15.2	75.7	80.2
70	80.6	46.2	21.2	75.7	78.7

A COMPARISON OF FIELD MEASUREMENTS FOR SLOPE ANGLE-AZPECT VARIATIONS AT DIFFERENT SOLAR ELEVATIONS

Field measurements were taken at solar elevations ranging from 11° to 62° in order to examine variations in the topographic effect. Comparison of the radiance measurements at different solar elevations (the extremes plotted in Figures 7 and 8) shows a considerable variation in sensor response. The largest deviation in red radiance values from the horizontal surface values was observed for the highest slopes oriented in the principal plane for all solar elevations. Deviations were maximized at low solar elevations for azpects of 0° (Figure 7) and at high solar elevations for azpects of 180° (Figure 8). Intermediate solar elevations exhibited equal variations for slopes into and away from the sun, i.e., in the principal plane (Figure 5).

Slopes with azpects from 0° to 90° had a greater range of relative red radiance values for the low solar elevations (Figure 7) than for high solar elevations (Figure 8). Slopes with azpects from 90° to 180° had a greater range of relative red radiance values for high solar elevation readings than for low solar elevation readings. The latter characteristic is explained by the sun being below the horizon for considerably more slopes. The data sets with intermediate solar elevations represented a gradation between the above two extremes of high and low solar elevation.

CORRELATION OF THE FIELD DATA WITH THE LAMBERTIAN MODEL

An example of cos Z' plots from the theoretical model (25 September, Figure 9) are presented for

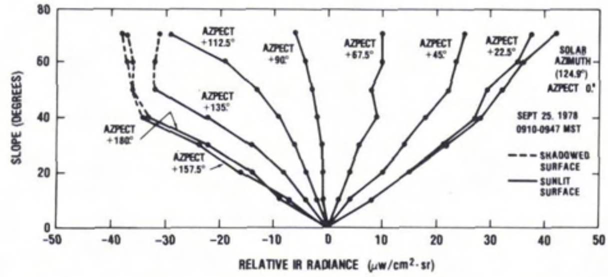

Fig. 6. Relative photographic infrared radiance field measurements for a solar elevation = 40°.

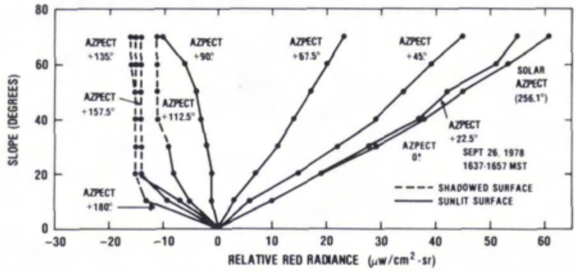

Fig. 7. Relative red radiance field measurements for a solar elevation = 11°.

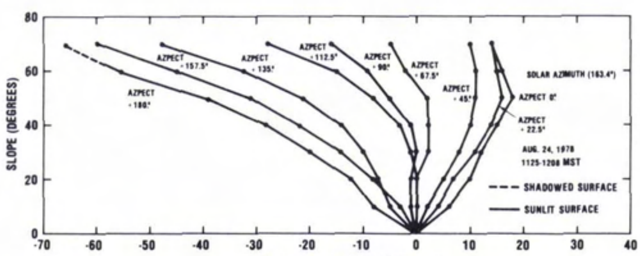

Fig. 8. Relative red radiance field measurements for a solar elevation = 62°.

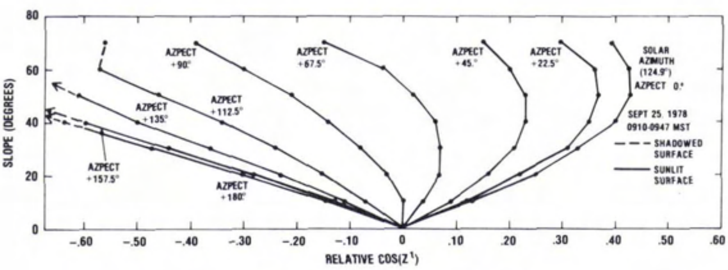

Fig. 9. Theoretical Z′ plots for 25 September.

comparison with the field measured radiances for the same data (Figure 5). In order to quantify the apparent similarity between the theoretical data and the field data, coefficients of determination, r^2, were calculated for each azpect string in the data sets (Table 2).

Coefficients of determination between the theoretical and actual data were found to be generally high, i.e., greater than 0.80 at the 5 percent significance level. Correlations were found to be highest for the lowest solar elevation, with coefficients of determination of greater than 0.85 for all azpect strings. Coefficients of determination were high for a solar elevation of 40°, except for azpects of 67° and 292° and 315°, i.e., for slopes oriented approximately perpendicular to the principal plane. Lowest correlations were found for the highest solar elevation data set, with azpects from 0°-90° having r^2 values of less than 0.80 (Table 2, 24 August). Low correlation coefficients were found to be associated with two major features of the data. First, low coefficients were calculated for azpect strings exhibiting little and irregular variation in radiance, e.g., plus or minus one or two relative radiance values, and thus correlation analysis was an unsatisfactory measure of association. Secondly, low coefficients were found at those azpect strings where the cos Z' values curved back on themselves (Figure 9, azpects 0° to 67.5°). Comparisons of Z' plots (Figure 9) and the field radiance values for 25 September (Figure 5) showed that the measured radiance values did not curve back on themselves as in the theoretical model, which was based on direct radiation only. The increase in measured radiance beyond the theoretical inflection point was thought to be due to the diffuse component, e.g., sky light and terrain reflection.

The correlation analysis shows that, for the particular sand surface measured, the Lambertian model was more highly correlated with azpect strings exhibiting the greatest radiance variation. The validity of the Lambertian assumption will, therefore, vary with azpect and may be applicable over a limited range of conditions. The degree to which the Lambertian assumption can be applied to the surface will depend on how the reflectance properties deviate from those of a Lambertian surface. To examine the non-Lambertian properties of the sand surface, i.e., the preferred orientations of scattering, the reflectance for each slope and azpect configuration was calculated (Figure 10). The reflectances were calculated for a 29° solar elevation by ratioing the radiance from the sand surface to that for the barium sulphate reference plate. The reflectances for the sand surface, although varying with slope and azpect, exhibited no marked orientation of scattering. Results presented by Coulson (1966) showed that reflectances from a dry sand surface in the principal plane exhibited a symmetry about the nadir.

It should be noted that the coefficient of determination, although giving a measure of association between the radiance and the theoretical model, provides only a general indication of the applicability of the model to simulating the radiances.

Table 2. Coefficients of Determination for Three Data Sets Corresponding to Low, Intermediate, and High Solar Elevations

	Coefficients of Determination (r^2)		
Aspect (°)	26 Sept 78 Solar Elevation = 11°	25 Sept 78 Solar Elevation = 40°	24 Aug 78 Solar Elevation = 62°
0	0.96*	0.75*	0.31⁺
22.5	0.96*	0.89*	0.07⁺
45	0.97*	0.65*	0.31⁺
67.5	0.88*	0.10⁺	0.60⁺
90	0.96*	0.98*	0.88*
112.5	ID	0.95*	0.86*
135	ID	0.98*	0.96*
157.5	ID	0.99*	0.98*
180	ID	0.99*	0.98*
202.5	ID	0.99*	ND
225	ID	0.99*	ND
247.5	1.00*	0.98*	ND
270	0.80*	0.94*	ND
292.5	0.93*	0.13⁺	ND
315	0.99*	0.06⁺	ND
337.5	0.99*	0.60*	ND

Key: * = Significant at the 5% level
\+ = Not significant at the 5% level
ND = No data
ID = Insufficient number of data points

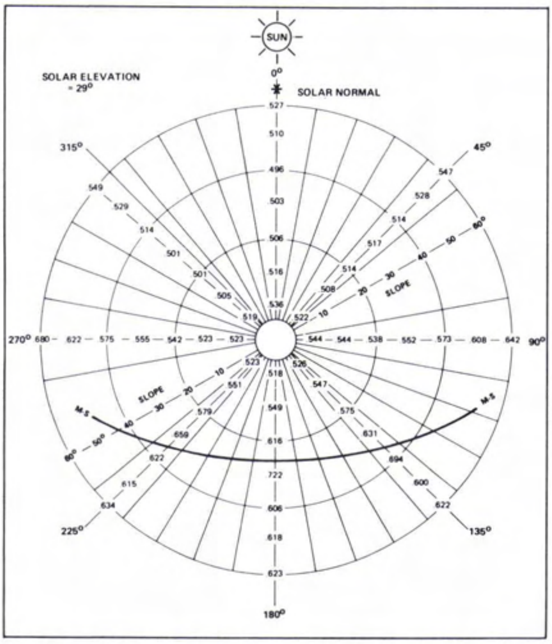

FIG. 10. Global reflectance (red channel) plotted by slope and azpect for a coarse sand surface. Demarkation of shadowed slopes (MS).

SIMULATION OF TOPOGRAPHIC INDUCED VARIATIONS IN LANDSAT SENSOR RESPONSE

The field data measured for the previous study quantified the topographic effect on the sensor response from the handheld radiometer. For the future application of theoretical radiance models to Landsat data, it is necessary to examine the topographic effect on the Landsat sensors. It was not possible to examine actual Landsat data relating to the measured surface, so an atmospheric radiative transfer model and a Landsat sensor simulation model were applied to the field data. Both of the models were developed by Dr. C. J. Tucker, Goddard Space Flight Center, and are described in detail by Tucker (1979). The atmospheric transmission model was based on a model described by Turner and Spencer (1972) and converted the field measured data into spectral path radiance and total spectral radiance at 706 km orbital altitude. For this study a horizontal visibility at sea level of 27 km was incorporated in the model to represent a low atmospheric aerosol content. The sensor simulation quantization model converted the spectral radiances into digital count output values at 128 levels for the red (0.63-0.69 μm) and 64 levels for the photographic infrared (0.76-0.90 μm) channels. These two channels are comparable to channels 5 and 7 of the existing Landsat MSS and correspond to the proposed Landsat-D Thematic Mapper bands 3 and 4.

The simulation models were applied to two subsets of the field data to calculate the theoretical Landsat pixel values for a range of Z' angles at two solar elevations (Table 3). For 25 September (solar elevation 40°) at azpects of 0° and 180° (i.e., the maximum variation in radiances), the simulated Landsat pixel values ranged from 14 to 66 for the red channel and 6 to 29 for the photographic infrared sensor. For 24 August (solar elevation 62°) the simulated Landsat values varied from 20 to 70 for the red channel and 7 to 31 for the photographic infrared. From these results it can be seen that at high solar elevations a range of 50 pixel values in the red channel could be associated with this surface over the range of slope angles and aspects measured. The implications of these results are that a wide range of pixel values can be expected for a given cover type in mountainous areas and that, unless the topographic effect is eliminated prior to or during classification, discrimination is likely to be undertaken with poor results.

TABLE 3. SIMULATED LANDSAT SENSOR RESPONSE (RED AND PHOTOGRAPHIC INFRARED) QUANTISED AT 128 AND 64 DIGITAL COUNT LEVELS RESPECTIVELY FOR Z' ANGLES AT LOW AND HIGH SOLAR ELEVATIONS

25 September Solar Elevation Angle = 40°			24 August Solar Elevation Angle = 62°		
Z' Angle (in degrees)	Quantization Level Red	I.R.	Z' Angle (in degrees)	Quantization Level Red	I.R.
90	14	6	90	20	7
80	24	10	87.7	26	10
70	30	13	77.7	38	15
60	36	16	67.7	46	18
55.4	40	17	57.7	52	21
50	42	19	47.7	56	24
45.4	46	20	37.7	60	24
35.4	52	22	28.6	64	27
25.4	54	24	27.7	66	29
15.4	60	26	18.6	68	29
5.4	62	27	8.6	68	30
4.6	66	29	1.4	70	31

Summary and Conclusions

The study presented in this paper describes a method for quantifying the topographic effect as measured from nadir pointing multispectral sensors.

The magnitude of the topographic effect was found to vary as a function of the solar elevation, the azimuthal orientation of the slope, and the slope inclination. The lowest solar elevations were found to produce the greatest contrast in radiance values from the range of slopes measured. Greatest variations in the sensor response were found for slopes oriented in the principal plane and least variation for those slopes oriented perpendicular to the principal plane.

The correlation analysis between the measured radiance and the theoretical model showed that the applicability of the Lambertian assumption varied within and between data sets. The lack of any prefered orientations of scattering from the sand surface provided an explanation for the generally high correlations between the radiances and the theoretical model. Although the Lambertian model will not completely simulate the radiances for all surface orientations of the sand surface, it may prove valid over a limited range of slope/aspect configurations. The correlation coefficients between the Lambertian model and the radiance for the sand surface proved substantially higher than those obtained for forested surfaces (Cicone *et al.*, 1977), and show that the appropriateness of the Lambertian assumption will vary considerably with cover type.

The implications of this study are that the topographic effect on Landsat data can produce a wide variation in the radiances associated with a given cover type. The simulation study showed a variation of as much as 52 pixel values in the red channel for a 40° solar elevation, for the range of slopes and surface examined in this study.

From this study it can be seen that, if slope angle, aspect, and solar zenith angle and azimuth are known, it may be possible to develop a technique incorporating a model to reduce the topographic effect prior to multispectral classification. It is currently possible to derive slope angle and aspect data from digital terrain data (McEwen and Elassal, 1976; Sharpnack and Akin, 1969; Strahler *et al.*, 1978), and the solar azimuth and elevation are provided with each Landsat scene. Development of this technique is being currently undertaken by the authors. An immediate recommendation for improvements in cover classification of mountainous areas is that multispectral classification should be undertaken for slope angle and aspect configurations within a given strata of cosine Z' values. This would in effect limit the range of radiances associated with a given cover type and would provide a considerable improvement over classification of a given cover type undertaken simply within a given aspect strata (Fleming *et al.*, 1975; Cicone *et al.*, 1977). It should be noted that for most practical applications of the solar incidence model to field areas, we would be concerned with smaller ranges of slope angles (e.g., 0-40°) than were examined in this study.

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1. Manuscripts should be typed, double-spaced on $8\frac{1}{2} \times 11$ or $8 \times 10\frac{1}{2}$ white bond, on *one* side only. References, footnotes, captions—everything should be double-spaced. Margins should be $1\frac{1}{2}$ inches.
2. Ordinarily *two* copies of the manuscript and two sets of illustrations should be submitted where the second set of illustrations need not be prime quality; EXCEPT that *five* copies of papers on Remote Sensing and Photointerpretation are needed, all with prime quality illustrations to facilitate the review process.
3. Each article should include an abstract, which is a *digest* of the article. An abstract should be 100 to 150 words in length.
4. Tables should be designed to fit into a width no more than five inches.
5. Illustrations should not be more than twice the final print size: *glossy* prints of photos should be submitted. Lettering should be neat, and designed for the reduction anticipated. Please include a separate list of captions.
6. Formulas should be expressed as simply as possible, keeping in mind the difficulties and limitations encountered in setting type.