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An Examination of Spectral Band Ratioing to Reduce the Topographic Effect on Remotely Sensed Data

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AN EXAMINATION OF SPECTRAL BAND RATIOING TO REDUCE THE TOPOGRAPHIC EFFECT ON REMOTELY SENSED DATA

by

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ABSTRACT

Spectral band ratioing in the form of $Radiance_i/Radiance_j$ was examined as a proposed means for reducing the topographic effect from multispectral data. The topographic effect is the differential illumination of sloping surfaces and results in surface cover types having a wide range of radiance values. A ground based nadir pointing two channel radiometer filtered for the red and photographic infrared portions of the electromagnetic spectrum was used to measure the topographic effect from a uniform surface inclined from horizontal to 60° at 16 compass points for several solar elevations.

Spectral band ratioing reduced the topographic effect by more than a factor of six (i.e., 83%) on the radiance data sets obtained in this study. The greatest proportional reduction of the topographic effect due to ratioing occurred where the topographic effect in the radiance was most pronounced, i.e., for slopes parallel to the principal plane, and least reduction for slope orientations perpendicular to the principal plane. A residual topographic effect was observed after ratioing the radiance data. This was reduced on an average of 50% for all slopes and aspects by subtracting the diffuse skylight component from the radiances.

Band ratioing of multispectral satellite and aircraft data can be expected to be less successful than results presented in this study due to a stronger effect of additive radiance factors. Even so, ratioing is a suitable technique for reducing the topographic effect in multispectral data and further refinements to spectral band ratioing are of questionable utility.

*Chris Justice is a National Research Council Resident Research Associate.

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1. INTRODUCTION

The "topographic effect" is manifested on Landsat multispectral images by the visual appearance of terrain ruggedness (Figure 1a) and is caused by the differential spectral radiance due to surface slope angle and aspect variations (Holben and Justice, 1979). The "topographic effect" is most pronounced in areas of rugged terrain and results in a wide range of radiance values for each cover type. The difference in radiance between a horizontal and sloping surface of the same cover type provides a measure of the topographic effect. Holben and Justice (1979) also showed that the degree of topographic effect on sensor response varies considerably as a function of solar elevation. This effect has been shown to greatly complicate the task of multispectral classification in mountainous areas (Hoffer and Staff, 1975; Cicone et al., 1977; Justice, 1978; Miller et al., 1978) and it is necessary to account for such variations either before or during classification (Kriegler et al., 1969; Strahler et al., 1978). Some studies have stated that the topographic effect can be reduced by ratioing spectral bands (Vincent, 1973; Goetz et al., 1975; Justice, 1978) and visual examination of ratioed Landsat images confirms this statement (Figure 1b).

Although quantitative analysis has shown the usefulness of band ratioing for vegetation studies (Jordon, 1969; Nalepka, 1970; Deering, 1975; Tucker, 1979; Tucker et al., 1979; and many others) and rock discrimination (Vincent, 1972, 1973; Goetz et al., 1975) there is little quantitative evidence to substantiate the statement that ratioing eliminates the topographic effect.

Quantitative analysis of the topographic effect on Landsat data is a complex task due to difficulties in ground location, variation in surface cover, and limited slope and aspect distributions. The authors, therefore, attempted to reduce some of the complexity by analyzing the topographic effect using radiance data collected with a nadir pointing hand-held radiometer from a unifrom sand surface inclined at various combinations of slope and aspect (Holben and Justice, 1979). This paper examines the effectiveness of ratioing the hand-held radiometer data for removing topographic-induced variations in the radiance measurements.

2. THE THEORY OF RATIOING

Ratioing of multispectral channels in its simplest form consists of dividing the radiance value in one channel by the corresponding radiance value in a second channel. Although more complex ratios are sometimes used (Deering, 1975; Tucker, 1979), the purpose for the techniques remains the same, namely, to reduce environmental effects and enhance the data. The rationale behind the use of ratios is rarely discussed in the literature though certain of the environmental effects have been examined in detail. For example, atmospheric effects have been well described in terms of the absorption and scattering processes of light, and have been modeled by Gates (1965), Dave and Furukama (1966), Turner and Spencer (1972), and many others. These atmospheric physicists have effectively described complete radiometric corrections to single band radiance data measured in the earth-atmosphere system. Kriegler et al., (1969) were among the first researchers to examine the application of the ratioing technique to such environmental effects. They defined the factors causing radiance variation as:

$$L_\lambda = \underbrace{E_\lambda(\theta, t)\, \rho_\lambda(\theta, t)\, T_\lambda(\theta, t)}_{\text{multiplicative term}} + \underbrace{\beta_\lambda(\theta, t)}_{\text{additive term}} \qquad (1)$$

Equation (After Kriegler et al., 1969)

where:

L_λ = Spectral radiance received at the sensor

$E_\lambda(\theta, t)$ = Direct spectral irradiance impinging the target at time t

$\rho_\lambda(\theta, t)$ = Target reflectance at time t

$T_\lambda(\theta, t)$ = Atmospheric transmittance at time t

$\beta_\lambda(\theta, t)$ = Scattered radiation by the atmosphere to the sensor's field of view at time t

θ = Angular parameters

Kriegler et al., (1969) and Crane (1971) categorized the factors causing radiance variation into multiplicative and additive terms. The multiplicative term is direct irradiance attenuated by quantifiable multiplicative environmental factors and as such is quantitative information. The additive term is so named as it is basically unquantified radiance (noise) added to the multiplicative term. The sum of the two terms is the total or global radiance, L_λ.

Vincent (1972) described the additive effects as a composition of two sources: diffuse light scattered into the path between the target and sensor by the atmosphere, and the diffuse light scattered into the sensor from the environment. Vincent (1972) states that the additive effects are usually ignored for ground or low altitude aircraft data, but should be removed for high altitude aircraft and satellite data. When ratioing, it should be noted that any additive radiance effects in two multispectral channels will cause a change in the ratioed value of the channels for the same target.

The multiplicative terms include atmospheric transmission, target reflectance and solar irradiance. For any one time, these factors have a complex angular interdependence. For example, the solar irradiance received at a surface is a function of sun angle, atmospheric path length and surface geometry. The radiance received by the sensor is in turn a function of the solar irradiance at the surface, target reflectance, sensor view angle and atmospheric transmission.

Kriegler et al., (1969), Crane (1971) and Vincent (1972) assumed that these angular interdependencies had equal multiplicative effects for all wavelengths, hence band ratioing of multispectral data was seen as a potentially powerful tool for reducing these multiplicative environmental effects on the radiance received at the sensor. The topographic effect, as a function of surface incidence and exitance angles of direct sunlight (Justice and Holben, 1979) is embodied within the multiplicative terms and therefore may be reduced by ratioing. Ratioing multispectral channels was demonstrated by the following example from Kriegler et al., (1969), in which the ratio of two adjacent narrow band channels is invariant for a given target. This example assumes all additive factors are negligible or have been subtracted out.

Consider a simple case in which the same target is sensed under two different sun-target-sensor geometries (A and B) with all other factors constant. The radiances (L) and, therefore, signals for channels i and j under conditions A and B are ratioed:

$$\frac{L_i^A}{L_j^A} \text{ and } \frac{L_i^B}{L_j^B}$$

Assuming an identical change in surface geometry occurs for each channel, then

$$L_i^A = kL_i^B$$

$$L_j^A = kL_i^B$$

for all multiplicative factors k. Then the two ratios are identical:

$$\frac{L_i^A}{L_j^A} = \frac{kL_i^B}{kL_j^B} = \frac{L_i^B}{L_j^B}$$

A similar argument can be made for any other combination of multiplicative factors.

3. DATA BASE AND METHODS

Our approach for examining the effect of ratioing on the topographic effect was to minimize the environmental variables which contribute to the additive terms and control those variables which contribute to the multiplicative terms. This was accomplished by employing a hand-held radiometer similar to that described by Pearson et al., (1976), to sense a uniform sand surface. The radiometer was filtered for the red (0.63 - 0.69μm) and photographic infrared (0.775 - 0.900μm) channels. The uniform sand surface was oriented to all combinations of slopes, ranging from 0 to 60° in 10° increments, and aspects ranging from 0 to 360° in 22.5° increments, for 11°, 35°, 40°, and 62° solar elevations. All observations were taken under cloudless conditions with a nadir pointing sensor. Less than one-half hour was required to complete collection of a data set, thereby reducing errors due to the apparent movement of the sun. All surrounding surfaces were painted black to eliminate any major scattering from adjacent sources. The surface aspect was measured in degrees, clockwise from the sun's azimuth. This angle is termed the "azpect" of the surface (Holben and Justice, 1979). Red and photographic infrared radiance data pairs were collected in data subsets called azpect strings, that is slopes of 0–60° for each azpect. An additional data set was collected to examine the effect of the scattered light additive factor on the ratioed data. The scattered light measurements were obtained by obscuring the solar disc, which is a standard method for collecting skylight data (Iqbal, 1979; Stanhill, 1966; Temps and Coulson, 1977). The global radiance (i.e., the total radiance impinging on the surface) was measured consecutively with the skylight data.

The radiance data were coded and ratio values were calculated for each observation pair. Means and standard deviations were calculated for all data sets and the results presented in the following section. For the additional data set the radiance measurements for the scattered light illuminated surface were subtracted from the global radiance measurements prior to analysis.

4. ANALYSIS

The object of this analysis was to determine whether ratioing of multispectral channels would reduce the topographic effect on sunlit surfaces. The approach of the analysis was to describe and examine the results of ratioing firstly, for a single solar elevation data set and secondly, for multiple solar elevation data sets with varying degrees of topographic effect. The ratio values of the two spectral channels were calculated for each radiance pair of the four data sets. These ratio values are presented with their associated red and photographic infrared radiances in the appendix.

The third part of the analysis examined ratioing as a means of reducing the topographic effect after the additive component had been removed, i.e., with the scattered light incident on the surface subtracted. This was achieved by isolating the direct sunlight component and calculating the resultant ratios.

5. RATIO VALUES AT A CONSTANT SUN ANGLE

If the assumption that ratioing eliminates the topographic effect holds true, then the ratio values calculated for each data set should be constant for all slope angle–aspect configurations.

Examination of the results shows that the ratio values were not constant within data sets. Several other general characteristics are evident from examination of the appendix. Ratio values generally increased with an increase in slope (Figure 2). Likewise, the standard deviations for the ratio values have a positive relationship with slope (Figure 3).

The topographic effect can be quantified by calculating the percent change in radiance for each slope from a reference radiance measurement. For this study the reference radiance was taken to be the radiance for a horizontal surface. To show the variation in the ratio values (i.e., the remaining topographic effect), the percentage change in the ratio value from the ratio for the horizontal surface was calculated for all azpects for a moderate solar elevation data set. The mean percentage change for each slope is plotted in Figure 4. The largest mean percentage change in ratio values (5%) was calculated for the 60° slope angle. Ratio values deviated less from the horizontal surface ratio for slopes perpendicular to the solar azimuth and more for slopes into and away from the solar azimuth (i.e , in the principal plane). These results show that the ratio values for different surface geometries were not constant and therefore it can be concluded that the topographic effect was not eliminated by ratioing.

Although ratioing has been shown not to eliminate the topographic effect, Figure 4 demonstrates that the topographic effect has been considerably reduced. In order to determine the degree of reduction in the topographic effect, it is necessary to compare the radiance data with the ratioed data. Examination of the radiance values in the appendix shows similar trends to the ratioed values. Both red and photographic infrared radiances increase with slope for azpects facing into solar azimuth. The percent change in the radiance values from the radiance for a horizontal surface was greatest for slopes in the principal plane and least for slopes oriented perpendicular to the principal plane. Calculation of the percentage change from the horizontal surface radiance for a moderate sun angle produced a maximum change of 40% in radiance for slopes of 10-60° (Figure 4).

To quantify the relationship between the ratioed and raw radiance values and thereby establish the degree of reduction in the topographic effect, we designed and calculated the Relative Normalization Factor (RNF) which is the percent change in the red radiance from the horizontal surface radiance divided by its associated percent change in the ratio values. The percent change in the red radiance was used in the calculation of the RNF but similar results would be expected from the photographic infrared radiance, because the correlation coefficients between the spectral channels were consistently greater than 0.97. Large RNF's indicate relatively good reduction or normalization of the topographic effect and small RNF's indicate poor reduction. An RNF of 1 indicates no change in the topographic effect in the ratioed and unratioed data and an RNF of greater than 1 indicates a reduction in the topographic effect. The calculated RNF's show that for the moderate solar elevation data set, the ratioed data reduced the topographic effect for all azpects (Table 1). The greatest reduction in the topographic effect was achieved for azpects in the principal plane.

Table 1
Table Showing Relative Normalization Factors for the Azpect Strings of the Moderate Sun Elevation Data Set

Azpect	0	45	90	135	180	225	270	315
RNF*	9	8	2	15	15	12	2	10

*RNF = (% change in Red Radiance)/(% change in Ratio Value)

For the data set shown above the RNF was calculated for slope classes from 0-60°. The RNF's for slopes of 10° and over were found to be relatively constant and showed the topographic effect to be reduced by an average factor of 8 (87%).

6. RATIOING AT SEVERAL SUN ANGLES

The descriptions in the previous section generally hold for all four solar elevation data sets examined in this study. Holben and Justice (1979) showed that the "topographic effect" could be measured by the magnitude of the differential radiance on sloping surfaces. Greater ranges in radiance over sloping surfaces were shown to occur at low sun elevation angles which produced greater topographic effects. The analysis in this section compares the ratio values between different solar elevation data sets, representing low, moderate, and high elevations (11°, 35°, 40°, and 62°).

Examination of the ratio values associated with the four solar elevations (Appendix) shows that the ratio values vary between data sets. These variations in ratios are summarized in Table 2, where the mean, standard deviation, and range of the ratios for each data set are presented.

Table 2
Summary of all Ratioed Observations for Each Data Set

Solar Elevation Date	62° 8/24/78	40° 9/25/78	35° 9/5/78	11° 9/26/78
Number of Azpect Strings	9	17	17	18
Mean Ratio Value	.889	.696	.880	.720
Standard Deviation of the Ratio Values	.0060	.0080	.0118	.0361
Range of Ratio Values	.88-.90	.68-.71	.86-.90	.67-.79

The smallest range in ratios (0.88–0.90) corresponded to the high solar elevation, i.e., the data set with the least topographic effect. The greatest range in ratios (0.67–0.79) corresponded to the low sun elevation data set, i.e., the greatest topographic effect. The range in ratioed values shows that the topographic effect was not totally normalized for any of the data sets.

To examine the remaining topographic effect within the ratioed data for the four solar elevations, the percentage change relative to the horizontal surface was calculated by slope classes for the ratio values and corresponding red radiances (Table 3). For all data sets, the percentage change within each slope category was smallest for the ratioed data, indicating a marked decrease in the topographic effect. The lowest remaining topographic effect occurred for the low solar elevation data set and the highest remaining topographic effect occurred for the high solar elevation data set. This is in keeping with the degree of topographic effect in the red radiance data for all four data sets (Table 3).

Table 3
Mean Percentage Change in Ratioed and Red Radiance Data
for Slope Categories

% Change in Slope	Sun El. = 62° 8/24/78		Sun El. = 40° 9/25/78		Sun El. = 35° 9/5/78		Sun El. = 11° 9/26/78	
	Ratio	Red Radiance	Ratio	Red Radiance	Ratio	Red Radiance	Ratio	Red Radiance
10	0.4	4.0	1.0	8.2	1.4	11.8	3.6	32.5
20	1.1	7.1	1.4	12.0	2.2	23.8	4.0	57.9
30	0.8	10.7	2.5	26.0	3.3	35.6	4.9	91.4
40	1.3	14.9	3.4	32.0	4.5	41.0	6.0	119.9
50	1.6	20.7	3.3	32.4	4.0	36.8	5.9	142.1
60	1.6	29.8	4.8	38.7	4.3	51.0	7.0	167.4

The RNF's were calculated for each solar elevation to compare the variations in the reduction of the topographic effect between data sets for each azpect (Table 4).

Table 4
Relative Normalization Factors (RNF) Calculated for the
Four Solar Elevation Data Sets

Azpect	Sun El. = 62° 8/24/78	Sun El. = 40° 9/25/78	Sun El. = 35° 9/5/78	Sun El. = 11° 9/26/78
0	11	9	14	120
45	10	8	22	14
90	1	2	1	4
135	14	15	18	21*
180	20*	15	6	10*
225	ND	12	11	23*
270	ND	2	3	<1
315	ND	10	13	15

*Value represents two or less data points.

Table 4 shows that the greatest reduction in the topographic effect occurs for the lowest solar elevation and for azpects in the principal plane.

To quantify the reduction in the topographic effect for all points in each data set, the coefficient of variation was calculated for both ratioed and unratioed data. The quotient of the two coefficients was then calculated for each data set, to derive a reduction factor. The smallest reduction was calculated for the high sun angle data set, for which ratioing reduced the topographic effect by a factor of 6 (83%).

7. RATIO VALUES WITH THE SCATTERED INCIDENT LIGHT SUBTRACTED

Light incident on a surface consists of both direct and scattered sunlight. Several studies have shown that the intensity and quality of scattered skylight is anisotropic under clear sky conditions, with a primary intensity maximum around the solar disc and a secondary intensity maximum around the solar horizon due to limb brightening of the earth (Bullrich et al., 1968; Kondratyev, 1977; Temps and Coulson, 1977). Justice and Holben (1980) show that the proportion of diffuse skylight as a percentage of the global irradiance varies with surface slope angle and aspect, the percentage diffuse light varying little for those slopes facing towards solar azimuth and greatest for those with high incidence angles. In section 6 the diffuse skylight was described as an additive term and theoretically could not be removed by ratioing. By measuring surface radiances for both global and scattered irradiance, it was possible to calculate the radiance ratios with the diffuse component subtracted to examine the effect on the variation in the ratioed data. Subtraction of the diffuse component from the radiance data led to approximately a 50% decrease in the standard deviation in the ratioed values for all azpect classes (Table 5). The degree of reduction was greatest, approximately 75%, for azpects perpendicular to the principal plane and least, approximately 20%, for azpect classes parallel to the principal plane.

Mean ratio values for each azpect class were observed to increase after the skylight component had been removed from the radiance data. This is attributed to the relatively greater

Table 5
Comparison of the Mean and Standard Deviations of the Global and Direct IR/RED Radiance Ratios

Azpect	Global IR/Red Ratio		n	Direct IR/Red Ratio	
	Mean	Std		Mean	Std
0	1.97	0.0421	14	2.09	0.0305
45	1.96	0.0421	7	2.07	0.0190
90	1.97	0.0606	7	2.03	0.0150
135	1.92	0.0663	5	2.00	0.0256
180	1.91	0.0759	4	2.00	0.0613
225	1.88	0.0783	5	1.96	0.0454
270	1.93	0.0844	7	2.01	0.0437
315	1.92	0.0617	7	2.02	0.0444

proportion of shorter wavelength radiation present in clear atmosphere skylight relative to direct light (Walsh, 1961). After the diffuse component is removed the relative proportion of the photographic infrared light increases resulting in higher ratio values.

The large decrease in the standard deviations of the direct light ratio values from the global light ratio values confirms that a substantial portion of the variation in global radiance ratios is due to skylight which we have termed "additive" and may not be removed by simple band ratioing.

8. DISCUSSION OF RESULTS

Ratioing of global radiances was shown to greatly reduce the topographic effect present in the radiance data. Greatest reduction of the topographic effect occurred for slopes in the principal plane, with high slope angles, and at high solar elevations (i.e., for slopes with the greatest topographic effect). A residual variation in the ratioed values was observed, which correspond to the topographic effect observed in the radiance data and was hypothesized to be due to the diffuse skylight irradiance. Elimination of this additive term (see Equation 1) further reduced the variation in the ratioed data. The reduction was greatest for slopes oriented perpendicular to the principal plane.

After subtraction of the diffuse skylight a smaller residual variation in the ratio values was observed. Three proposed explanations for the remaining residual variation are presented. First, the surface reflectance properties are non-Lambertian (Holben and Justice, 1979) and by definition have preferred scattering orientations. If the directional reflectance properties of the surface are significantly wavelength dependent, this will militate against complete reduction of the topographic effect by spectral band ratioing. Second, measurement error may have contributed to the variations in the ratios. Third, the additive terms described in section 6 may not have been completely removed by the experimental method.

Two types of additive radiance terms were identified as possible sources of remaining variation in the ratioed data; scattered radiation from the surrounding terrain and scattered radiation from the atmosphere. Terrain scattering was minimized by the experimental method (section 7).

The remaining atmospheric additive radiance terms can be categorized into radiance scattered into the sensor from the surrounding atmosphere, and radiance due to variations in atmospheric path length. The former was minimal in the case of these ground measurements. The variation in the atmospheric path length causing changes in the spectral intensity of light measured for each data set may in part explain the difference in the ratio values between the data sets. Under clear sky conditions, the proportion of diffuse light varies with solar elevation (Justice and Holben, 1980) which would contribute to variations in the ratios between the data sets.

9. CONCLUSIONS AND IMPLICATIONS

a. Ratioing did not completely eliminate the topographic effect within the field measured radiance data.

b. Ratioing reduced the topographic effect in the radiance data for the range of slopes (0–60°) and solar elevations (11–62°) examined by an average of 83%.

c. The remaining topographic effect within the ratioed data was due to uncorrected additive radiance terms.

d. Subtracting the scattered light component of the global irradiance prior to ratioing was shown to further reduce the topographic effect.

e. The proposed explanation for the small remaining variation in the ratioed data with the diffuse light subtracted was the wavelength dependency of the scattering properties of the surface.

f. Ratioing will not be effective for reducing the topographic effect on shaded surfaces which are illuminated solely by scattered light.

From this study, certain implications can be made concerning the application of the ratioing technique to multispectral satellite data. Firstly, ratioing of multispectral channels is perhaps the simplest technique for reducing a large proportion of the topographic effect within multispectral satellite data. Secondly, direct inference from these results to those that can be expected from ratioing satellite data should be made with great care. Certain of the additive terms minimized in this study will play an important part in confounding the reduction in topographic effect on satellite data. For example, light scattered from adjacent slopes will undoubtedly make an important contribution to the incident radiance, particularly in areas of rugged terrain (Kimes, 1980). Light scattered into the sensor from the surrounding atmosphere will also affect the ratio from satellite radiance data. These additive terms may lead to somewhat less satisfactory results than obtained by this study. Thirdly, complete removal of the scattered skylight component cannot be achieved when using multispectral satellite data, although subtraction of a mean diffuse value obtainable from known shaded surfaces may lead to some improvement in reducing the ratio variations. The degree of improvement achievable by this method makes the utility of reduction of the diffuse component somewhat questionable.

Results from this study show that ratioing will be most effective for areas of extreme ruggedness exhibiting a marked topographic effect, although it will be obvious that many parts of the world have few slopes of greater than 30° and the topographic effects exhibited by the radiance data used in this study will rarely be so extreme. The advantages and disadvantages of using the resulting ratioed data for cover type discrimination are outside the immediate scope of this study.

From this study it can be seen that the effectiveness of ratioing for removing the topographic effect is a complex matter and in any area will be dependent on a number of interrelated factors, e.g., sun angle, spatial distribution of slopes, angles and orientations, skylight and atmospheric conditions and surface cover types. Even so it is clear that ratioing offers a good and usually adequate first reduction of the topographic effect and further refinements of the technique are of questionable utility.

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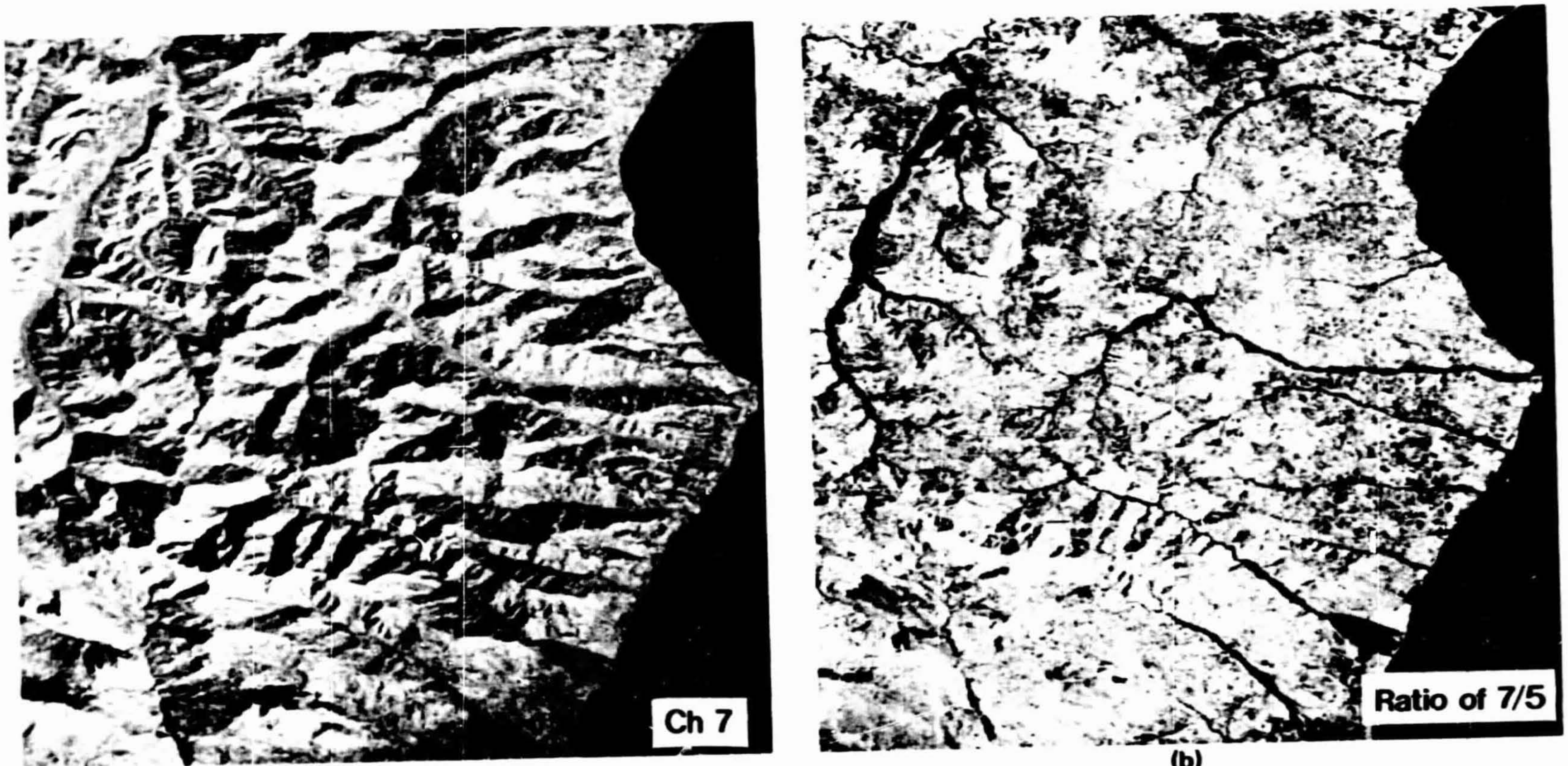

(a) (b)

Figure 1. A Scene of Mountainous Terrain for: (a) an Unprocessed Channel 7 Image and (b) a Ratioed 7/5 Image of the Same Area. Note the Visual Appearance of Topographic Relief in (a) and the Flat Appearance in (b) Indicating a Marked Decrease in the Topographic Effect.

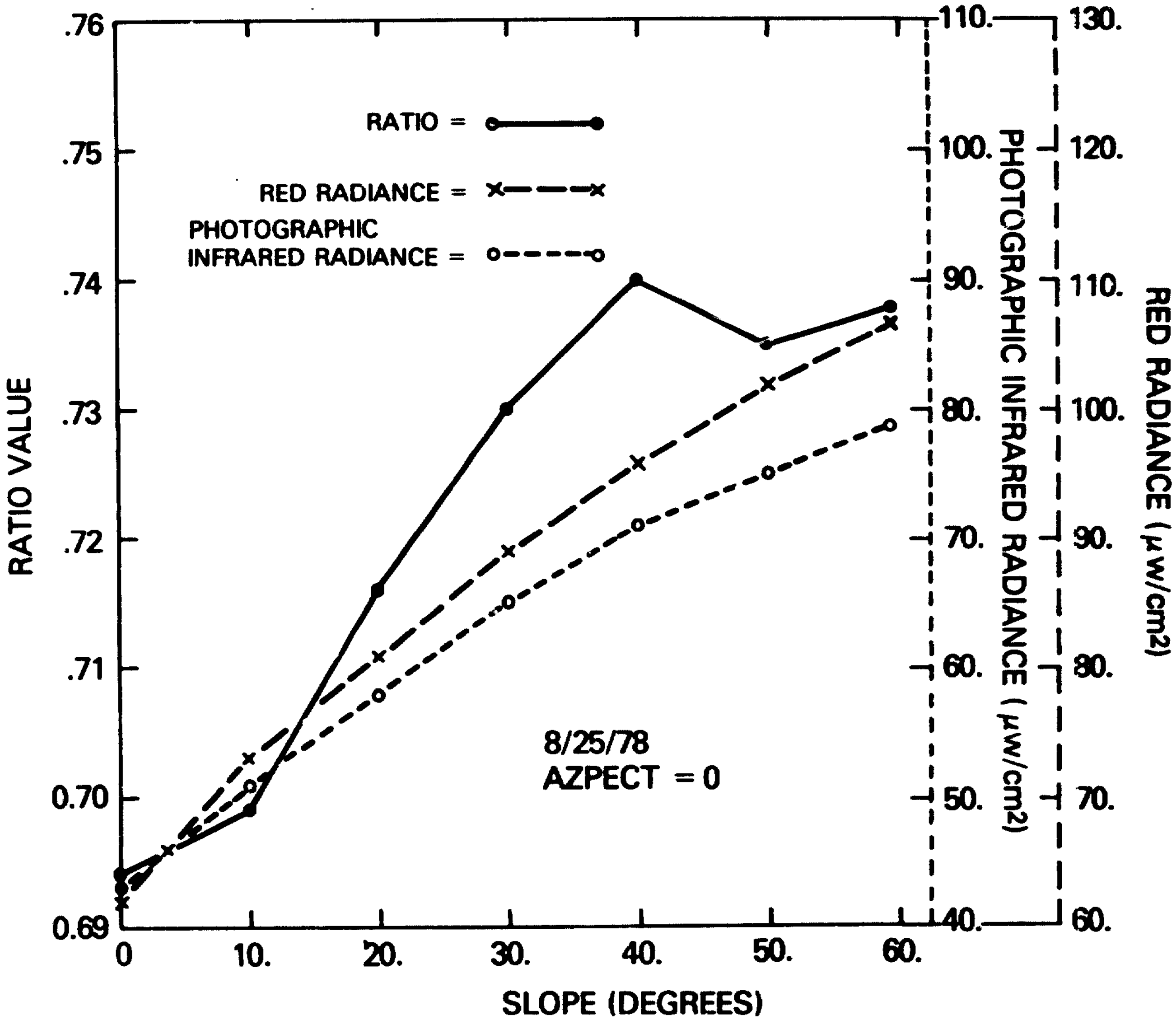

Figure 2. Figure to Show Red and Photographic Infrared Radiance and Ratio Values Plotted Against Slope

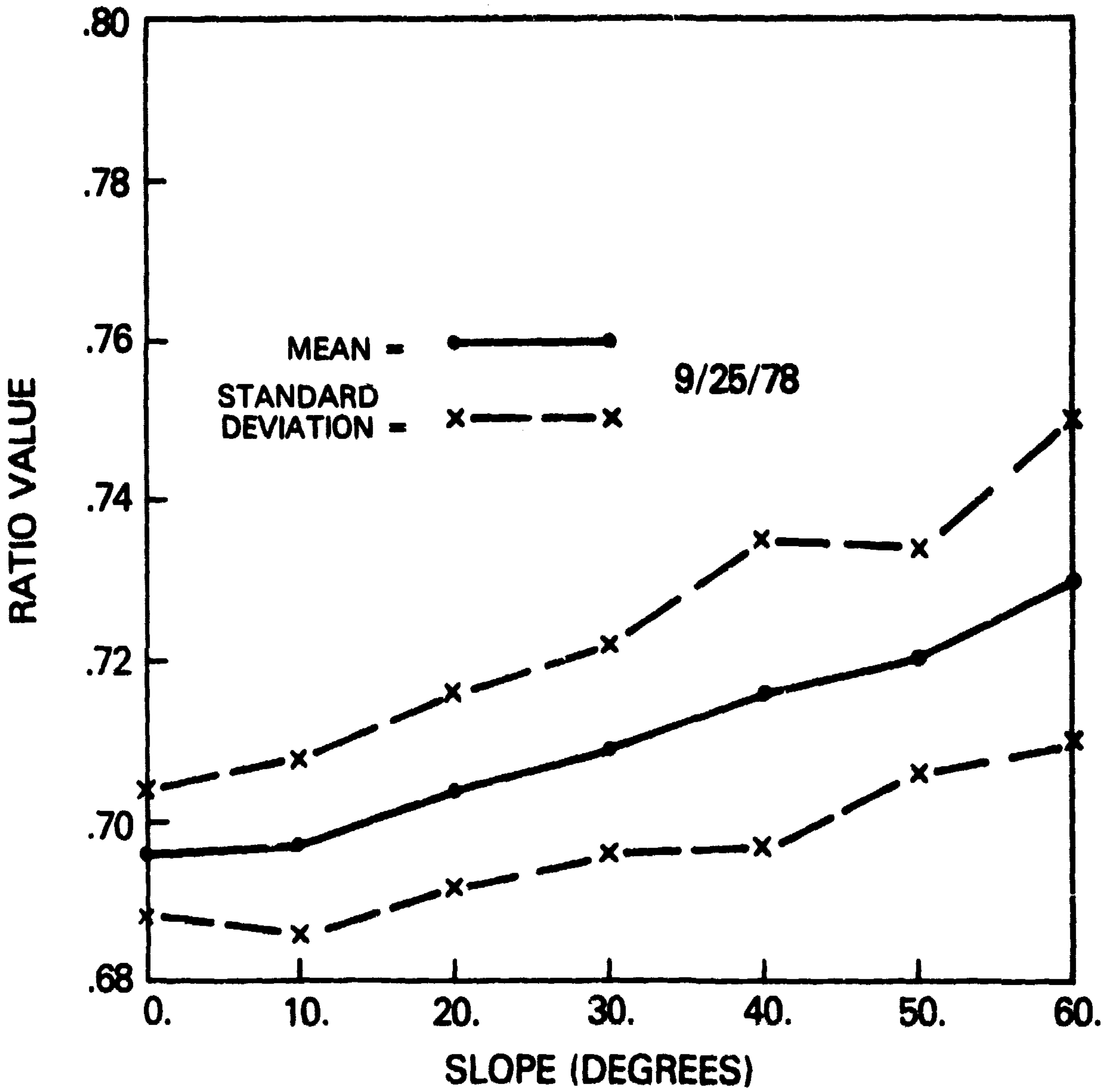

Figure 3. The Standard Deviations of the Ratio Values Plotted Against Slope

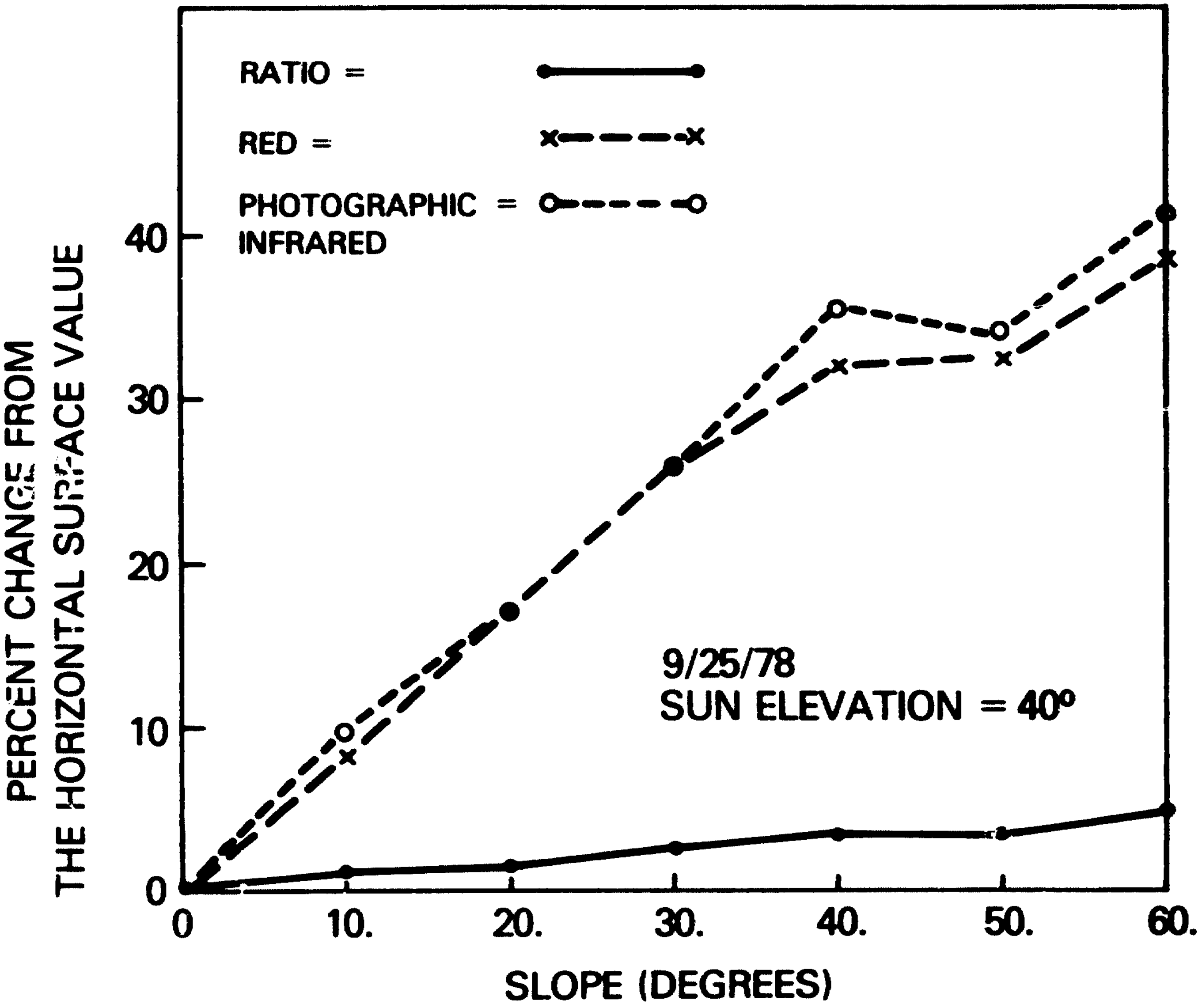

Figure 4. The Mean Percent Change in Ratios Plotted for Each Slope Value

APPENDIX

8/24/78 Sun Elevation Angle = 62°

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
1	0	80	71	0.0	0.89	32	50	76	67	90.0	0.88
2	10	86	77	0.0	0.89	33	60	72	64	90.0	0.89
3	20	90	81	0.0	0.90	34	0	78	70	112.5	0.90
4	30	92	83	0.0	0.90	35	10	78	70	112.5	0.90
5	40	95	85	0.0	0.89	36	20	78	68	112.5	0.87
6	50	98	85	0.0	0.87	37	30	77	68	112.5	0.88
7	0	79	70	22.5	0.89	38	40	75	66	112.5	0.88
8	10	83	74	22.5	0.89	39	50	70	62	112.5	0.88
9	20	86	77	22.5	0.89	40	60	63	56	112.5	0.89
10	30	90	79	22.5	0.88	41	0	83	74	135.0	0.89
11	40	93	82	22.5	0.88	42	10	78	69	135.0	0.88
12	50	95	85	22.5	0.89	43	20	76	67	135.0	0.88
13	0	82	73	45.0	0.89	44	30	73	64	135.0	0.88
14	10	84	75	45.0	0.89	45	40	69	60	135.0	0.87
15	20	87	78	45.0	0.90	46	50	62	54	135.0	0.87
16	30	90	80	45.0	0.89	47	60	51	46	135.0	0.90
17	40	92	82	45.0	0.89	48	0	80	71	157.5	0.89
18	50	93	82	45.0	0.88	49	10	77	68	157.5	0.88
19	60	93	82	45.0	0.88	50	20	72	65	157.5	0.90
20	0	82	72	67.5	0.88	51	30	66	59	157.5	0.89
21	10	82	73	67.5	0.89	52	40	58	53	157.5	0.91
22	20	84	74	67.5	0.88	53	50	49	45	157.5	0.92
23	30	84	74	67.5	0.88	54	60	35	32	157.5	0.91
24	40	84	74	67.5	0.88	55	0	83	73	180.0	0.88
25	50	84	74	67.5	0.88	56	10	75	66	180.0	0.88
26	60	80	70	67.5	0.87	57	20	71	62	180.0	0.87
27	0	81	72	90.0	0.89	58	30	63	55	180.0	0.87
28	10	80	71	90.0	0.89	59	40	55	48	180.0	0.87
29	20	80	71	90.0	0.89	60	50	44	40	180.0	0.91
30	30	81	71	90.0	0.89	61	60	27	25	180.0	0.92
31	40	80	69	90.0	0.86						

APPENDIX

9/25/78   Sun Elevation Angle = 40°

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
1	0	62	43	0.0	0.69	33	40	62	44	90.0	0.71
2	10	73	51	0.0	0.70	34	50	59	43	90.0	0.73
3	20	81	58	0.0	0.72	35	60	55	42	90.0	0.76
4	30	89	65	0.0	0.73	36	0	65	45	112.5	0.69
5	40	96	71	0.0	0.74	37	10	62	43	112.5	0.69
6	50	102	75	0.0	0.73	38	20	59	41	112.5	0.69
7	60	107	79	0.0	0.74	39	30	55	39	112.5	0.71
8	0	61	42	22.5	0.69	40	40	50	36	112.5	0.72
9	10	71	50	22.5	0.70	41	50	43	32	112.5	0.74
10	20	80	57	22.5	0.71	42	60	34	26	112.5	0.76
11	30	88	63	22.5	0.72	43	0	66	46	135.0	0.70
12	40	95	69	22.5	0.73	44	10	60	42	135.0	0.70
13	50	99	71	22.5	0.72	45	20	54	38	135.0	0.70
14	60	104	77	22.5	0.74	46	30	45	32	135.0	0.71
15	0	65	45	45.0	0.69	47	40	32	24	135.0	0.75
16	10	70	49	45.0	0.70	48	0	69	48	157.5	0.70
17	20	77	55	45.0	0.71	49	10	58	39	157.5	0.67
18	30	83	59	45.0	0.71	50	20	46	34	157.5	0.74
19	40	88	63	45.0	0.72	51	30	38	26	157.5	0.68
20	50	92	67	45.0	0.73	52	0	71	49	180.0	0.69
21	60	94	68	45.0	0.72	53	10	60	42	180.0	0.70
22	0	65	45	67.5	0.69	54	20	47	33	180.0	0.70
23	10	68	47	67.5	0.69	55	30	36	26	180.0	0.72
24	20	70	49	67.5	0.70	56	0	71	49	202.5	0.69
25	30	72	51	67.5	0.74	57	10	60	41	202.5	0.68
26	40	75	54	67.5	0.72	58	20	53	36	202.5	0.68
27	50	74	53	67.5	0.72	59	30	42	29	202.5	0.69
28	60	76	54	67.5	0.71	60	40	26	19	202.5	0.73
29	0	66	46	90.0	0.70	61	0	71	50	225.0	0.70
30	10	65	45	90.0	0.69	62	10	67	46	225.0	0.69
31	20	64	45	90.0	0.70	63	20	59	41	225.0	0.69
32	30	64	45	90.0	0.70	64	30	51	35	225.0	0.69

APPENDIX

9/25/78 Sun Elevation Angle = 40° (Continued)

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
65	40	41	28	225.0	0.68	87	0	77	55	315.0	0.71
66	0	73	51	247.5	0.70	88	10	80	57	315.0	0.71
67	10	70	49	247.5	0.70	89	20	82	59	315.0	0.72
68	20	68	47	247.5	0.69	90	30	89	64	315.0	0.72
69	30	61	43	247.5	0.70	91	40	95	69	315.0	0.73
70	40	56	39	247.5	0.70	92	50	101	73	315.0	0.72
71	50	48	34	247.5	0.71	93	60	103	77	315.0	0.75
72	60	36	26	247.5	0.72	94	0	79	56	337.5	0.71
73	0	75	52	270.0	0.69	95	10	86	61	337.5	0.71
74	10	77	54	270.0	0.70	96	20	94	67	337.5	0.71
75	20	76	53	270.0	0.70	97	30	101	71	337.5	0.70
76	30	74	52	270.0	0.70	98	40	106	76	337.5	0.72
77	40	73	51	270.0	0.70	99	50	110	79	337.5	0.72
78	50	71	50	270.0	0.70	100	60	114	83	337.5	0.73
79	60	68	48	270.0	0.71	101	0	81	57	0.0	0.70
80	0	79	55	292.5	0.70	102	10	89	63	0.0	0.71
81	10	82	58	292.5	0.71	103	20	97	68	0.0	0.70
82	20	86	60	292.5	0.70	104	30	103	73	0.0	0.71
83	30	89	63	292.5	0.71	105	40	108	77	0.0	0.71
84	40	90	64	292.5	0.71	106	50	110	78	0.0	0.71
85	50	91	64	292.5	0.70	107	60	114	81	0.0	0.71
86	60	91	65	292.5	0.71						

APPENDIX

9/5/78 Sun Elevation Angle = 35°

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
1	0	44	38	0.0	0.86	33	40	47	43	90.0	0.91
2	10	56	50	0.0	0.89	34	50	44	42	90.0	0.95
3	20	65	58	0.0	0.89	35	60	40	38	90.0	0.95
4	30	71	64	0.0	0.90	36	0	52	46	112.5	0.88
5	40	79	71	0.0	0.90	37	10	48	43	112.5	0.90
6	50	81	75	0.0	0.93	38	20	45	40	112.5	0.89
7	60	87	79	0.0	0.91	39	30	40	36	112.5	0.90
8	0	46	41	22.5	0.89	40	40	34	31	112.5	0.91
9	10	54	49	22.5	0.91	41	50	26	25	112.5	0.96
10	20	62	56	22.5	0.91	42	0	53	47	135.0	0.89
11	30	69	64	22.5	0.93	43	10	47	41	135.0	0.87
12	40	76	70	22.5	0.92	44	20	39	35	135.0	0.90
13	50	82	76	22.5	0.93	45	30	30	27	135.0	0.90
14	60	85	79	22.5	0.93	46	40	17	17	135.0	1.00
15	0	47	42	45.0	0.89	47	0	54	48	157.5	0.89
16	10	54	49	45.0	0.91	48	10	46	41	157.5	0.89
17	20	61	55	45.0	0.90	49	20	35	32	157.5	0.91
18	30	67	61	45.0	0.91	50	30	23	21	157.5	0.91
19	40	72	67	45.0	0.93	51	0	54	47	180.0	0.87
20	50	75	69	45.0	0.92	52	10	46	41	180.0	0.89
21	60	78	72	45.0	0.92	53	20	31	29	180.0	0.93
22	0	48	42	67.5	0.87	54	30	20	19	180.0	0.95
23	10	51	45	67.5	0.88	55	0	56	49	202.5	0.87
24	20	54	48	67.5	0.89	56	10	48	42	202.5	0.87
25	30	56	51	67.5	0.91	57	20	37	33	202.5	0.89
26	40	58	53	67.5	0.91	58	30	24	22	202.5	0.92
27	50	61	56	67.5	0.92	59	0	58	50	225.0	0.86
28	60	61	56	67.5	0.92	60	10	51	44	225.0	0.86
29	0	48	42	90.0	0.88	61	20	43	38	225.0	0.88
30	10	49	44	90.0	0.90	62	30	30	28	225.0	0.93
31	20	49	45	90.0	0.92	63	40	20	18	225.0	0.90
32	30	48	44	90.0	0.92	64	0	58	51	247.5	0.88

APPENDIX

9/5/78 Sun Elevation Angle = 35° (Continued)

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
65	10	54	47	247.5	0.87	86	10	67	59	315.0	0.88
66	20	50	43	247.5	0.86	87	20	73	64	315.0	0.88
67	30	44	38	247.5	0.86	88	30	77	68	315.0	0.88
68	40	37	37	247.5	1.00	89	40	81	72	315.0	0.89
69	50	28	25	247.5	0.89	90	50	84	74	315.0	0.88
70	60	19	18	247.5	0.95	91	60	86	72	315.0	0.84
71	0	59	51	270.0	0.86	92	0	59	52	337.5	0.88
72	10	57	49	270.0	0.86	93	10	68	60	337.5	0.88
73	20	57	49	270.0	0.86	94	20	74	66	337.5	0.89
74	30	57	49	270.0	0.86	95	30	81	72	337.5	0.89
75	40	58	50	270.0	0.86	96	40	87	77	337.5	0.88
76	50	57	50	270.0	0.88	97	50	92	82	337.5	0.89
77	60	48	42	270.0	0.88	98	60	96	85	337.5	0.89
78	0	59	51	292.5	0.86	99	0	61	54	0.0	0.89
79	10	62	54	292.5	0.87	100	10	70	62	0.0	0.89
80	20	64	56	292.5	0.87	101	20	78	70	0.0	0.90
81	30	66	58	292.5	0.87	102	30	84	75	0.0	0.89
82	40	69	60	292.5	0.87	103	40	90	81	0.0	0.90
83	50	71	63	292.5	0.89	104	50	95	85	0.0	0.89
84	60	69	61	292.5	0.88	105	60	98	89	0.0	0.91
85	0	60	53	315.0	0.88						

APPENDIX

9/26/78 Sun Elevation Angle = 11°

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
1	0	28	21	0.0	0.75	33	40	54	40	45.0	0.74
2	10	38	28	0.0	0.74	34	50	59	44	45.0	0.74
3	20	47	35	0.0	0.74	35	60	64	48	45.0	0.75
4	30	57	43	0.0	0.75	36	0	24	17	67.5	0.71
5	40	66	49	0.0	0.74	37	10	26	19	67.5	0.73
6	50	73	55	0.0	0.75	38	20	31	22	67.5	0.71
7	60	81	61	0.0	0.75	39	30	35	26	67.5	0.74
8	0	18	14	0.0	0.78	40	40	38	28	67.5	0.74
9	10	27	21	0.0	0.78	41	50	41	30	67.5	0.73
10	20	37	29	0.0	0.78	42	60	44	33	67.5	0.75
11	30	45	35	0.0	0.78	43	0	23	16	90.0	0.70
12	40	54	43	0.0	0.80	44	10	22	16	90.0	0.73
13	50	61	48	0.0	0.79	45	20	22	16	90.0	0.73
14	60	68	54	0.0	0.79	46	30	21	15	90.0	0.71
15	0	14	11	0.0	0.79	47	40	20	15	90.0	0.75
16	10	22	17	0.0	0.77	48	50	19	14	90.0	0.74
17	20	30	24	0.0	0.80	49	60	17	13	90.0	0.76
18	30	37	30	0.0	0.81	50	0	23	16	112.5	0.70
19	40	44	37	0.0	0.84	51	10	18	12	112.5	0.67
20	50	49	41	0.0	0.84	52	20	14	9	112.5	0.64
21	60	56	47	0.0	0.84	53	0	22	15	135.0	0.68
22	0	26	18	22.5	0.69	54	10	15	10	135.0	0.67
23	10	36	26	22.5	0.72	55	0	21	15	157.5	0.71
24	20	45	33	22.5	0.73	56	10	12	8	157.5	0.67
25	30	53	40	22.5	0.75	57	0	21	14	180.0	0.67
26	40	63	47	22.5	0.75	58	10	8	5	180.0	0.62
27	50	68	51	22.5	0.75	59	0	16	12	202.5	0.75
28	60	76	57	22.5	0.75	60	10	8	5	202.5	0.62
29	0	25	17	45.0	0.68	61	0	17	13	225.0	0.76
30	10	31	23	45.0	0.74	62	10	12	9	225.0	0.75
31	20	40	29	45.0	0.72	63	0	14	10	247.5	0.71
32	30	47	35	45.0	0.74	64	10	12	9	247.5	0.75

APPENDIX

9/26/78 Sun Elevation Angle = 11° (Continued)

Obs.	Slope	Red	P.IR	Azpect	Ratio	Obs.	Slope	Red	P.IR	Azpect	Ratio
65	20	10	7	247.5	0.70	80	0	18	13	315.0	0.72
66	0	19	13	270.0	0.68	81	10	24	18	315.0	0.75
67	10	19	13	270.0	0.68	82	20	30	23	315.0	0.77
68	20	19	14	270.0	0.74	83	30	36	28	315.0	0.78
69	30	19	14	270.0	0.74	84	40	42	32	315.0	0.76
70	40	19	14	270.0	0.74	85	50	46	36	315.0	0.78
71	50	20	15	270.0	0.75	86	60	51	40	315.0	0.78
72	60	20	16	270.0	0.80	87	0	16	12	337.5	0.75
73	0	15	11	292.5	0.73	88	10	24	19	337.5	0.79
74	10	18	14	292.5	0.78	89	20	33	26	337.5	0.79
75	20	22	17	292.5	0.77	90	30	40	32	337.5	0.80
76	30	26	20	292.5	0.77	91	40	47	38	337.5	0.81
77	40	29	23	292.5	0.79	92	50	53	42	337.5	0.79
78	50	32	26	292.5	0.81	93	60	58	46	337.5	0.79
79	60	36	29	292.5	0.81						