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Radiometric Resolution For Monitoring Vegetation
How Many Bits Are Needed?

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RADIOMETRIC RESOLUTION FOR MONITORING VEGETATION
HOW MANY BITS ARE NEEDED?*

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CONTENTS

TABLES

TABLES (CONTINUED)

ILLUSTRATIONS

ILLUSTRATIONS (CONTINUED)

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ABSTRACT

The significance of the various number of radiometric quantizing levels required for satellite monitoring of vegetation resources was evaluated by using *in situ* collected spectral reflectance data, an atmospheric radiative transfer simulation model, and a satellite sensor simulation model. Reflectance data were converted to radiance data; passed through a model atmosphere to an altitude of 706 km; and subsequently quantized at 16, 32, 64, 128, 256, and 512 digital count levels for Thematic Mapper bands TM3 (0.63–0.69 μm) and TM4 (0.76–0.90 μm). The simulated digital count data were regressed against the *in situ* biological data to quantify the relationship between quantizing levels.

Results of the analysis demonstrated that solar zenith angle had an effect on $NE\Delta\rho$ (as expected), that 256 quantizing levels gave a 2-3% improvement per channel over 64 quantizing levels,* and that 256 quantizing levels gave a 1% improvement per channel over 128 quantizing levels. No improvements were found for 256 vs. 512 quantizing levels.

*Recall that the Thematic Mapper is currently designed to provide 256 levels without gain change while the older Landsat MSS data provide only 64 levels.

RADIOMETRIC RESOLUTION FOR MONITORING VEGETATION HOW MANY BITS ARE NEEDED?

INTRODUCTION

Radiometric resolution for satellite monitoring of vegetation involves the conversion of remotely sensed spectral radiances into some type of output signal from the sensor system in question. Usually this output signal is converted from an analog voltage to a digital binary word for telemetry to ground stations. In the case of the Landsat Multispectral Scanner (MSS), each of the four reflective bands receives spectral radiances which are in turn converted into digital count outputs ranging from 0 to 63. The MSS has six-bit radiometric accuracy or, in other words, quantizes input radiances among 64 levels. Various analog gains are provided to match the scene dynamic range to the capability of the quantizer. Radiances which exceed the full range value are output as level 63.

The full range value is selected as the maximum radiance value which the sensor system will experience for the band in question under various illumination conditions. The interval between quantizing levels is simply the maximum radiance value divided by the number of quantizing levels minus one. In the case of the MSS, there are 63 radiance quantizing levels and level 1 which is zero.

Previous efforts to address the question of satellite sensor system radiometric resolution have approached this problem by using aircraft multispectral scanner data (Morgenstern et al., 1976). The procedure used for this type of radiometric resolution investigation involved using a simulation classifier and a set of scene cover-type spectral responses for an agricultural data set collected by an aircraft multispectral scanner. These data were employed to define decision boundaries for the various scene components. Pixels in the simulated scene were randomly generated from each of the spectral response distributions and were subsequently classified. Radiometric sensitivity was simulated by adding corresponding amounts of noise to the covariance matrices of the spectral responses. Conclusions of this simulation included that a noise equivalent change in reflectance ($NE\Delta\rho$)* of

*The $NE\Delta\rho$ of the Landsat MSS is ~2% while the Thematic Mapper will have a $NE\Delta\rho$ of ~0.5% for the first four reflective bands.

0.5% to 2.0% resulted in an overall decrease in classification accuracy from 87% to 80%, a classification accuracy decrease from 53% to 37% for highly stressed corn, and a classification accuracy decrease from 94% to 85% for soybeans. These simulation results addressed the specific question of how field center classification accuracy was affected by changes in NE$\Delta\rho$. The authors caution that actual classification or mensuration accuracy is a complex function of many factors, only one of which is field center accuracy (Morgenstern et al., 1976).

NE$\Delta\rho$, as used in this report refers to the change in target spectral reflectance necessary to result in a spectral radiance value which is quantized by the sensor system in question into a higher or lower output signal vis-a-vis an "unchanged" or noiseless target spectral reflectance. Where

$$\text{NE}\Delta\rho = \left\{ \frac{\text{(scene radiance)}}{\text{(mean sensor signal)/(rms sensor noise)}} \right\} \cdot \left\{ \frac{1}{\frac{\partial\,\text{(scene radiance)}}{\partial\rho}} \right\} \qquad (1)$$

and

$$\text{NE}\Delta\rho = \left\{ \text{NE radiance} \right\} \cdot \left\{ \frac{\partial\rho}{\partial\,\text{radiance}} \right\} \qquad (2)$$

with ρ = spectral reflectance of target

NE = noise equivalent of sensor (i.e., generally electronic and quantizing noise)

rms = root mean square

The NE$\Delta\rho$ thus represents the ability of a sensor system to detect a minimum change in target spectral reflectance (or NEΔT for thermal channels). The smaller the numerical value for the NE$\Delta\rho$ or NEΔT, the more sensitive any sensor system is to changes in target spectral radiances. Several factors besides quantization levels impact upon a sensor system's NE$\Delta\rho$ performance. These factors include the intensity of the target incident spectral irradiance (solar zenith angle and atmospheric conditions) and the nature of the sensor system's optical and electronic design.

A brief review of how target spectral radiances are sensed by a satellite multispectral scanner system is necessary to understand the relationship of radiometric resolution to overall system performance.

Target spectral radiances are in part reflected upward and, with the addition of atmospheric backscattered spectral radiances, both impinge upon the sensor's detectors at the satellite system's orbital altitude. In general the spectral radiances are converted by the detectors into an output signal (current or voltage) which is amplified and passed through a low-pass presample filter. The low-pass filter controls (1) the rms electronic noise; and (2) the high frequency aliasing due to targets smaller than a resolution element. Recall that the Nyquist theorem states that the total information in a band limited signal can be reconstructed if sampling occurs at 2 times the highest frequency component. Therefore, the low-pass presample filter minimizes the effect of high spatial frequency targets which can appear "aliased" as lower frequencies within the filter bandpass.

Electronic sampling then occurs to obtain voltage (analog) values for each pixel which are representative of the scene radiances. This sampled voltage is next converted from an analog level into a digital value by the analog/digital converter. This is a straightforward task where the input voltage is converted into the binary representation of the voltage level to which it most closely corresponds. The various bands for the system in question are multiplexed and encoded serially into a data stream which is telemetered directly or recorded for subsequent telemetry to ground receiving stations.

The number of quantizing levels impacts upon the data rate transmitted from the satellite to ground receiving stations. Because of the relationship of the number of bands, the spatial resolution, and various aspects of sensor system performance to the resulting data rate, detailed understanding of radiometric resolution will allow for instrument design trade-offs to be made for optimum system performance. These are related by the equation:

$$\text{DATA RATE} = \frac{(\frac{v}{h}) \cdot \theta \cdot s \cdot g \cdot b}{K_s \cdot \alpha^2} \quad (3)$$

where

DATA RATE = BITS/SECOND
v = speed relative to ground

h = altitude
θ = viewing angle
s = samples per IFOV
g = quantizing levels
b = number of bands
K_s = scanning efficiency (i.e., TM = 0.85, MSS = 0.45)
α = angular IFOV

DESCRIPTION OF RESEARCH UNDERTAKEN

The work described herein was undertaken to explore and quantify the relationship between the number of quantizing levels of a satellite remote sensing system and the ability of that system to resolve detailed spectral information related to physiologic condition from vegetated surfaces. A new approach was taken where *in situ* collected reflectance data, computed radiance data for the orbital altitude of the sensor system in question, and simulated digital count satellite scanner system output for 16, 32, 64, 128, 256, and 512 quantizing levels were evaluated. These relationship(s) were quantified statistically by regressing the spectral variables against sampled plant canopy biological data. Comparison of coefficients of determination (r^2 values) then allowed for quantifying the improvement(s)/degradation(s) resulting from the different quantizing levels.

The research described in this report addressed the specific question of how many quantifying levels or number of bits were required for earth resource satellite missions which monitor vegetation resources. To accomplish this end, Landsat-D Thematic Mapper bands TM3 (0.63-0.69 μm) and TM4 (0.76-0.90 μm) were selected for detailed radiometric resolution study. TM3 was selected because it received spectral radiances which are very low in energy as a result of chlorophyll absorption in the 0.63-0.69 μm region. TM4 was selected because it receives spectral radiances which are very high in energy as a result of the high levels of foliar spectral reflectance characteristic of green vegetation. These two bands then represented the two extremes in the 0.40-2.50 μm spectral region for remote sensing of vegetation missions.

This study addresses the question of radiometric resolution for monitoring vegetation condition and not classification accuracy. It is assumed, however, that remote sensing radiometric resolution requirements for monitoring vegetation and classification of vegetation types are similar. This follows in that differences between types of vegetation result from differences in morphological expression which are usually associated with differences in vegetation geometry, biomass, chlorophyll density, projected leaf area, foliar water density, etc.

METHODS-ANALYSIS

Three *in situ* collected data sets were used for this study. They included a September 1971 grassland data set, an April 1978 winter wheat data set, and a May 1978 data set (Figure 1; Table 1). The three data sets were selected because they represented a range of different reflectance values and also represent data from a natural ecological scene (the grassland data) and agricultural scenes (the winter wheat data).

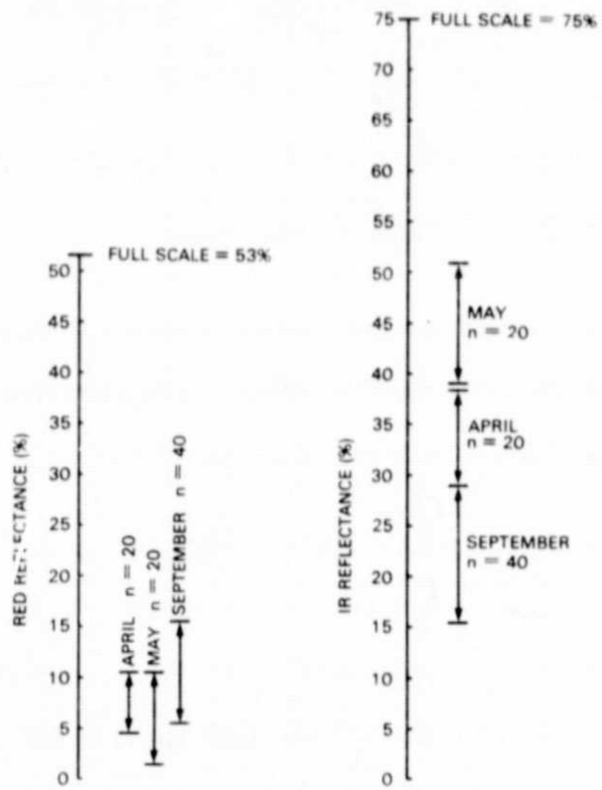


Figure 1. Reflectance values used for the three data sets for TM3 (0.63-0.69 μm) and TM4 (0.76-0.90 μm). The April, 1978 and May, 1978 data sets are from winter wheat while the September, 1971 data set is from blue grama grass.

TABLE 1

Statistical Summary of Reflectances and Canopy Variable Characteristics for the Three Data Sets Evaluated. (A) The April 1978 winter wheat data set; (B) The May 1978 winter wheat data set; and (C) The September 1971 blue grama grass data set.

	VARIABLE	SAMPLE SIZE	MEAN	STND. DEV.	RANGE	STND. ERROR OF MEAN	COEFF. OF VARIATION
A	RED REFL. (%)	20	7.26	1.53	4.38-10.63	0.34	21.04
	IR REFL. (%)	20	33.74	2.18	28.70-37.70	0.49	6.45
	TOTAL DRY BIOMASS (g/m^2)	20	795.02	152.51	480.78-1004.50	34.10	19.18
B	RED REFL. (%)	20	5.63	2.03	3.13-10.50	0.45	36.03
	IR REFL. (%)	20	43.98	3.54	38.70-51.61	0.79	8.05
	TOTAL DRY BIOMASS (g/m^2)	20	795.02	152.51	480.78-1004.50	34.10	19.18
C	RED REFL. (%)	40	11.90	2.47	6.27-15.98	0.39	20.72
	IR REFL. (%)	40	21.30	3.34	15.60-28.57	0.53	15.69
	LEAF WATER CONTENT (g/m^2)	40	92.75	50.93	28.03-190.80	8.05	54.91

The three data sets were used to provide *in situ* reflectance data for Landsat-D Thematic Mapper bands TM3 (0.63–0.69 μm) and TM4 (0.76–0.90 μm).

Satellite sensor bands receive spectral radiances according to their spectral configuration. The *in situ* data used for this analysis are spectral reflectance data and thus conversions were made to express the spectral reflectance data as spectral radiance data.

To accomplish this, an atmospheric transmission model was used where each of the spectral reflectances were illuminated by a computed spectral irradiance value at sea level. The resulting spectral radiance then was passed directly overhead to a 706 km orbital altitude. Data input values to the atmospheric model included the mid-band reflectances of TM3 and TM4 (i.e., the reflectance data; Table 1), twelve solar zenith angles (Table 2), and a horizontal visibility at sea level of 27 km (Tinkler and Reini, 1973).

TABLE 2

Coefficient of Determination (r^2) Values Resulting from the Regressions Between the Spectral Variables for Five Solar Zenith Angles and Total Dry Biomass for the April 1978 Data. TM3 = 0.63–0.69 μm, TM4 = 0.76–0.90 μm, ND = (TM4–TM3)/(TM4+TM3), and RATIO = TM4/TM3.

SPECTRAL VARIABLE	SOLAR ZENITH ANGLE (DEGREES)	NUMBER OF QUANTIZING LEVELS						RADIANCES AT 706 KM	INPUT REFLECTANCES
		4	5	6	7	8	9		
TM3	54.2	0.46	0.46	0.62	0.70	0.69	0.71	0.70	0.70
TM3	40.27	0.48	0.49	0.67	0.72	0.72	0.70	0.70	0.70
TM3	34.62	0.47	0.64	0.75	0.65	0.70	0.70	0.70	0.70
TM3	27.68	0.45	0.50	0.67	0.65	0.71	0.70	0.70	0.70
TM3	17.65	0.47	0.64	0.71	0.70	0.71	0.70	0.70	0.70
TM4	54.2	0.21	0.62	0.65	0.78	0.75	0.79	0.77	0.77
TM4	40.27	0.25	0.53	0.69	0.78	0.79	0.77	0.77	0.77
TM4	34.62	0.47	0.70	0.75	0.75	0.77	0.77	0.77	0.77
TM4	27.68	0.52	0.64	0.78	0.78	0.77	0.77	0.77	0.77
TM4	17.65	0.40	0.62	0.74	0.77	0.77	0.77	0.77	0.77
ND	54.2	0.54	0.59	0.72	0.82	0.80	0.81	0.81	0.81
ND	40.27	0.44	0.58	0.78	0.80	0.81	0.80	0.81	0.81
ND	34.62	0.68	0.75	0.85	0.76	0.80	0.80	0.81	0.81
ND	27.68	0.59	0.68	0.78	0.79	0.81	0.80	0.81	0.81
ND	17.65	0.57	0.77	0.81	0.81	0.81	0.81	0.81	0.81
RATIO	54.2	0.52	0.52	0.67	0.72	0.71	0.73	0.72	0.72
RATIO	40.27	0.33	0.53	0.68	0.72	0.73	0.72	0.71	0.72
RATIO	34.62	0.69	0.64	0.79	0.67	0.73	0.72	0.72	0.72
RATIO	27.68	0.57	0.65	0.68	0.71	0.72	0.72	0.72	0.72
RATIO	17.65	0.53	0.70	0.74	0.74	0.73	0.73	0.73	0.72

The atmospheric radiative transfer model which was used for this analysis was based on the Turner and Spencer (1972) model. This simulation program calculates the spectral path radiance and the total spectral radiance at any altitude in the earth's atmosphere according to a modified 2-stream radiative-transfer function. The path radiance is a function of the solar zenith angle, the nadir view angle, the azimuth angle between the vertical solar plane and the vertical view plane, the horizontal visibility at sea level, the surface background spectral reflectance, and the target spectral reflectance. The horizontal visibility at sea level was a surrogate for the atmospheric aerosol concentration.

The atmosphere was treated as being plane-parallel, horizontally homogeneous, and non-absorbing which was bounded by a spatially uniform Lambertian surface (Tinkler and Reini, 1973). It was therefore well suited for evaluating the 0.63-0.69 and 0.76-0.90 μm bands used in this analysis.

The reflectance data did not correspond exactly to the TM3 and TM4 mid-band reflectances. The September 1971 data used were 0.675 μm for TM3 and 0.765 μm for TM4. The April and May 1976 data used were collected with 0.65-0.70 μm and 0.775-0.825 μm bands. Although the data used in this analysis do not correspond exactly to TM3 and TM4 data, in every case they fall within or extremely close to the Thematic Mapper 0.63-0.69 and 0.76-0.90 μm bands evaluated. Previous research by the author has demonstrated that no spectral constraints were violated by the approach used herein (Tucker 1978).

The radiance data at 706 km were remotely sensed by a computer program which converted the spectral radiances into digital count output values for 16, 32, 64, 128, 256, and 512 quantizing levels (i.e., 4, 5, 6, 7, 8, and 9 bits). This was done for TM3 by using the saturation target reflectance value of 53% for a solar zenith angle of 22° and a clear rural atmosphere horizontal visibility of 27 km. The saturation target reflectance value of 75% was used for TM4 with the identical atmospheric conditions. Ten percent was added to each maximum saturation to bring each value exactly in line with the Thematic Mapper specifications for TM3 and TM4 (Duck 1979).

The conversions of the TM3 and TM4 input radiances at 706 km into digitized counts were considered to be noise-free. The author acknowledges that noise is introduced by the sensor electronics and the quantizing process but these considerations lie outside the scope of this paper. It should be remembered, however, that "quantizing noise" was present in the reflectance data used in this analysis.

The September 1971 spectral reflectance data were regressed against the leaf water content (after Tucker 1977) while the April and May 1978 spectral data were regressed against the total dry biomass (after Tucker et al., 1979).

RESULTS – DISCUSSION

The first portion of the analysis was to quantify the relationships between the four spectral reflectance variables and the respective plant canopy biological variables for the three data sets (Figure 2; Tables 3, 4, and 5). It was inherent in this study that one could not improve upon the baseline reflectance data as that data served as the basis for the simulations which followed.

The radiance data at 706 km for each of the solar zenith angles evaluated were identical in a regression sense to the reflectance data (Figure 3; Tables 3, 4, and 5). This would be expected because the radiance data are simply a scalar product of the reflectance data for the various atmospheric conditions evaluated.

The conversion of the spectral radiance data at 706 km into digital count data was illustrated graphically in Figure 4. Radiance data were presented to the sensor in question and were subsequently quantized to the radiance level which was closest in equivalence to its radiance value. The satellite system then outputs a binary code value (or digital count) for an integer from 0 to 63 corresponding to the quantizing level closest in equivalence to the input radiance value (Figure 4). It

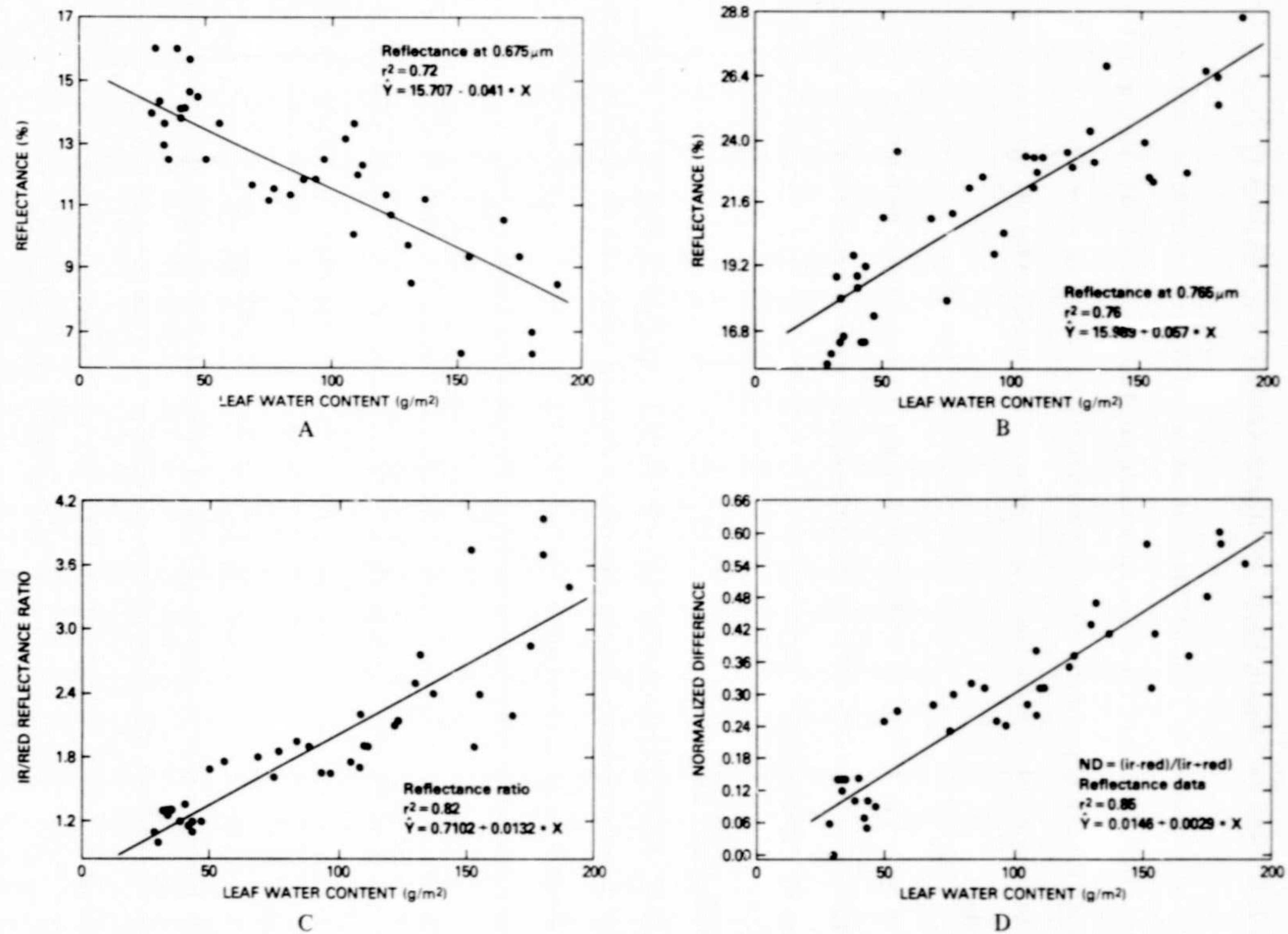


Figure 2. Reflectance data and associated linear combinations for the September, 1971 grassland data. Reflectance at (A) 0.675 μm and (B) 0.765 μm. The 0.765 μm/0.675 μm reflectance ratio appears as (C) and the reflectance normalized differences as (D). These represent the reflectance data used in the analysis.

TABLE 3

Coefficient of Determination (r^2) Values Resulting from the Regressions Between the Spectral Variables for Five Solar Zenith Angles and Total Dry Biomass for the May, 1978 Data. TM3 = 0.63–0.69 μm, TM4 = 0.76–0.90 μm, ND = (TM4–TM3)/(TM4+TM3), and RATIO = TM4/TM3.

SPECTRAL VARIABLE	SOLAR ZENITH ANGLE (DEGREES)	NUMBER OF QUANTIZING LEVELS						RADIANCES AT 706 KM	INPUT REFLECTANCES
		4	5	6	7	8	9		
TM3	54.2	0.47	0.63	0.65	0.69	0.72	0.74	0.73	0.73
TM3	40.27	0.65	0.60	0.69	0.70	0.73	0.72	0.73	0.73
TM3	34.62	0.41	0.70	0.77	0.73	0.72	0.73	0.73	0.73
TM3	27.68	0.45	0.59	0.76	0.73	0.73	0.73	0.73	0.73
TM3	17.65	0.56	0.68	0.74	0.72	0.73	0.72	0.73	0.73
TM4	54.2	0.38	0.73	0.67	0.69	0.67	0.67	0.67	0.67
TM4	40.27	0.59	0.69	0.67	0.67	0.68	0.67	0.67	0.67
TM4	34.62	0.59	0.69	0.69	0.65	0.68	0.67	0.67	0.67
TM4	27.68	0.59	0.67	0.65	0.69	0.68	0.68	0.67	0.67
TM4	17.65	0.60	0.68	0.68	0.66	0.67	0.67	0.67	0.67
ND	54.2	0.63	0.77	0.73	0.77	0.79	0.80	0.79	0.79
ND	40.27	0.70	0.70	0.77	0.77	0.79	0.79	0.79	0.79
ND	34.62	0.52	0.78	0.81	0.78	0.79	0.79	0.79	0.79
ND	27.68	0.56	0.70	0.80	0.80	0.79	0.79	0.79	0.79
ND	17.65	0.74	0.75	0.80	0.79	0.79	0.79	0.79	0.79
RATIO	54.2	0.65	0.70	0.65	0.71	0.72	0.72	0.71	0.71
RATIO	40.27	0.61	0.61	0.72	0.68	0.71	0.70	0.70	0.71
RATIO	34.62	0.37	0.73	0.70	0.71	0.70	0.71	0.71	0.71
RATIO	27.68	0.41	0.62	0.71	0.72	0.71	0.71	0.71	0.71
RATIO	17.65	0.79	0.64	0.73	0.72	0.71	0.71	0.71	0.71

TABLE 4

Coefficient of Determination (r^2) Values Resulting from the Regressions Between the Spectral Variables for Five Solar Zenith Angles and Leaf Water Content for the September, 1971 Data. TM3 = 0.63–0.69 μm, TM4 = 0.76–0.90 μm, ND = (TM4–TM3)/(TM4+TM3), and RATIO = TM4/TM3.

SPECTRAL VARIABLE	SOLAR ZENITH ANGLE (DEGREES)	NUMBER OF QUANTIZING LEVELS						RADIANCES AT 706 KM	INPUT REFLECTANCES
		4	5	6	7	8	9		
TM3	54.2	0.50	0.59	0.70	0.71	0.72	0.72	0.72	0.72
TM3	40.27	0.50	0.69	0.72	0.71	0.72	0.72	0.72	0.72
TM3	34.62	0.60	0.70	0.71	0.72	0.72	0.72	0.72	0.72
TM3	27.68	0.59	0.66	0.71	0.72	0.72	0.72	0.72	0.72
TM3	17.65	0.49	0.68	0.68	0.71	0.72	0.72	0.72	0.72
TM4	54.2	0.67	0.60	0.74	0.77	0.76	0.76	0.76	0.76
TM4	40.27	0.41	0.72	0.75	0.76	0.76	0.76	0.76	0.76
TM4	34.62	0.68	0.77	0.78	0.75	0.76	0.76	0.76	0.76
TM4	27.68	0.71	0.66	0.74	0.76	0.77	0.76	0.76	0.76
TM4	17.65	0.48	0.67	0.76	0.76	0.77	0.76	0.76	0.76
ND	54.2	0.74	0.77	0.84	0.85	0.85	0.86	0.85	0.85
ND	40.27	0.61	0.81	0.86	0.85	0.85	0.85	0.85	0.85
ND	34.62	0.78	0.85	0.84	0.86	0.85	0.85	0.85	0.85
ND	27.68	0.77	0.79	0.84	0.85	0.85	0.86	0.85	0.85
ND	17.65	0.62	0.82	0.84	0.85	0.86	0.85	0.85	0.85
RATIO	54.2	0.70	0.76	0.81	0.82	0.82	0.82	0.82	0.82
RATIO	40.27	0.61	0.80	0.84	0.81	0.82	0.82	0.82	0.82
RATIO	34.62	0.76	0.82	0.80	0.83	0.82	0.82	0.82	0.82
RATIO	27.68	0.73	0.76	0.81	0.82	0.82	0.82	0.82	0.82
RATIO	17.65	0.58	0.78	0.80	0.82	0.83	0.82	0.82	0.82

TABLE 5

Coefficient of Determination (r^2) Values Resulting from the Regressions Between the Spectral Variables for Five Solar Zenith Angles and the Leaf Water Content for Perfectly Correlated TM3 and TM4 Reflectance Data. These Reflectance Data were Generated by the Regression Equations in Figures 2a and 2b. TM3 = 0.63–0.69 μm, TM4 = 0.76–0.90 μm, ND = (TM4–TM3)/(TM4+TM3), and RATIO = TM4/TM3.

SPECTRAL VARIABLE	SOLAR ZENITH ANGLE (DEGREES)	NUMBER OF QUANTIZING LEVELS						RADIANCES AT 706 KM	INPUT REFLECTANCES
		4	5	6	7	8	9		
TM3	54.2	0.63	0.77	0.97	0.99	1.00	1.00	1.00	1.00
TM3	40.27	0.58	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM3	34.62	0.83	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM3	27.68	0.76	0.92	0.99	0.99	1.00	1.00	1.00	1.00
TM3	17.65	0.67	0.94	0.98	0.99	1.00	1.00	1.00	1.00
TM4	54.2	0.76	0.81	0.97	0.99	1.00	1.00	1.00	1.00
TM4	40.27	0.70	0.91	0.98	0.99	1.00	1.00	1.00	1.00
TM4	34.62	0.76	0.94	0.98	0.99	1.00	1.00	1.00	1.00
TM4	27.68	0.86	0.93	0.98	0.99	1.00	1.00	1.00	1.00
TM4	17.65	0.66	0.92	0.99	1.00	1.00	1.00	1.00	1.00
ND	54.2	0.80	0.90	0.98	0.99	1.00	1.00	1.00	1.00
ND	40.27	0.74	0.96	0.98	1.00	1.00	1.00	1.00	1.00
ND	34.62	0.91	0.93	0.99	1.00	1.00	1.00	1.00	1.00
ND	27.68	0.91	0.95	0.99	1.00	1.00	1.00	1.00	1.00
ND	17.65	0.68	0.98	0.99	1.00	1.00	1.00	1.00	1.00
RATIO	54.2	0.81	0.89	0.96	0.98	0.98	0.98	0.98	0.98
RATIO	40.27	0.73	0.94	0.96	0.98	0.98	0.98	0.98	0.98
RATIO	34.62	0.90	0.95	0.97	0.98	0.98	0.98	0.98	0.98
RATIO	27.68	0.93	0.91	0.98	0.98	0.98	0.98	0.98	0.98
RATIO	17.65	0.70	0.97	0.98	0.98	0.98	0.98	0.98	0.98

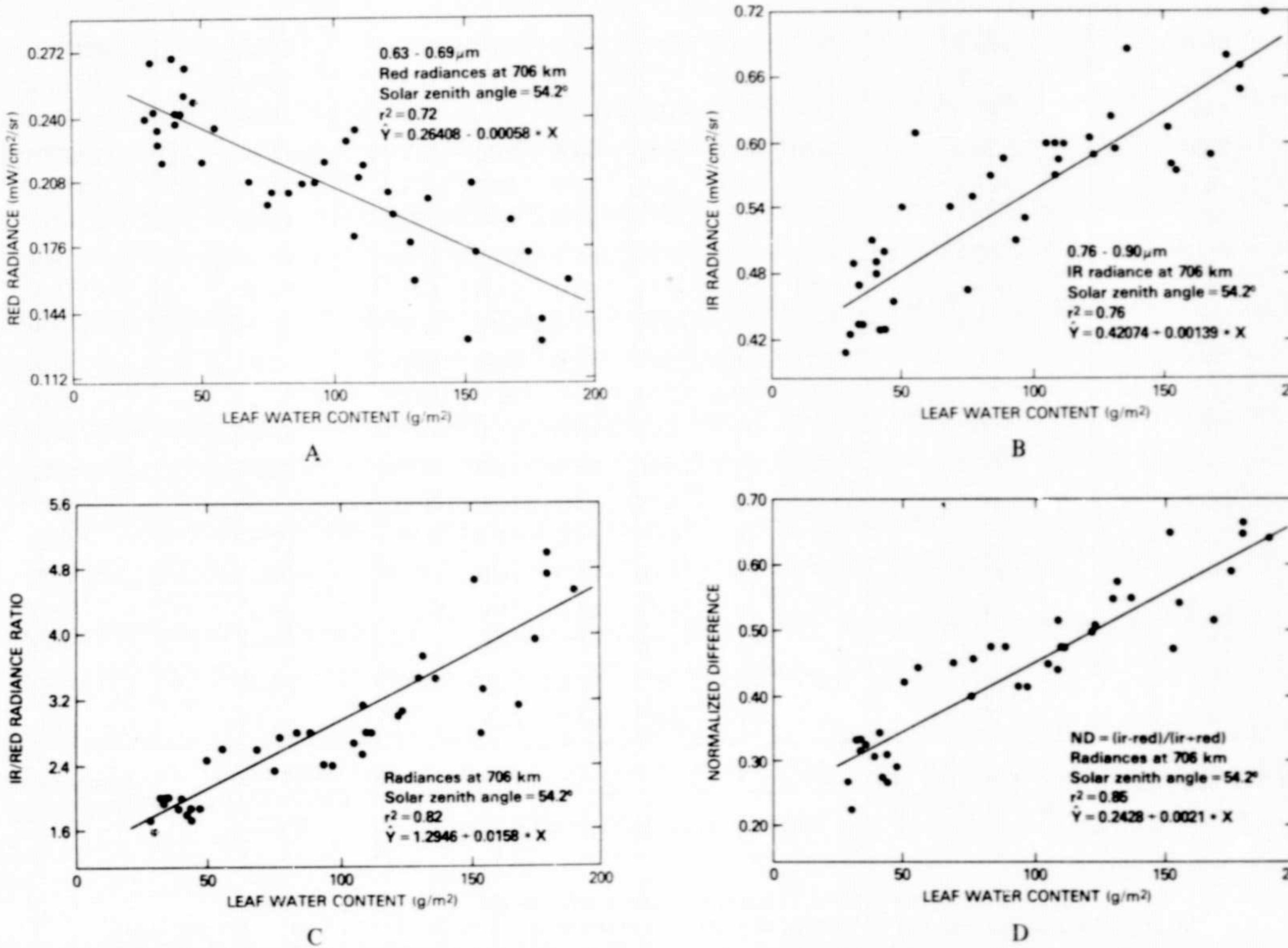
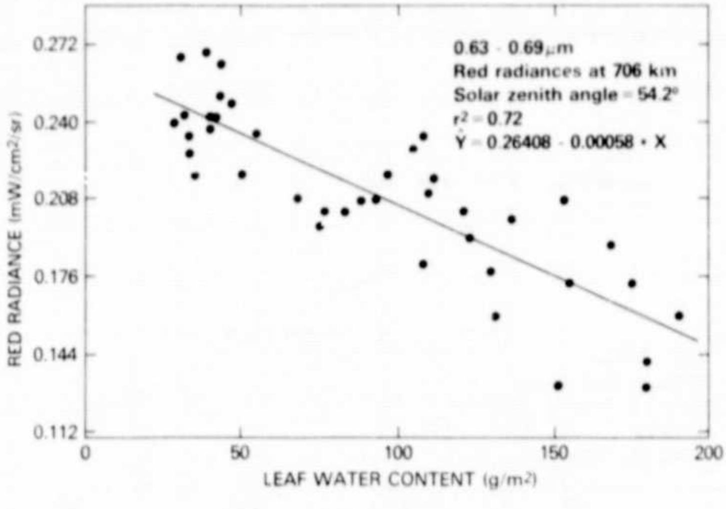
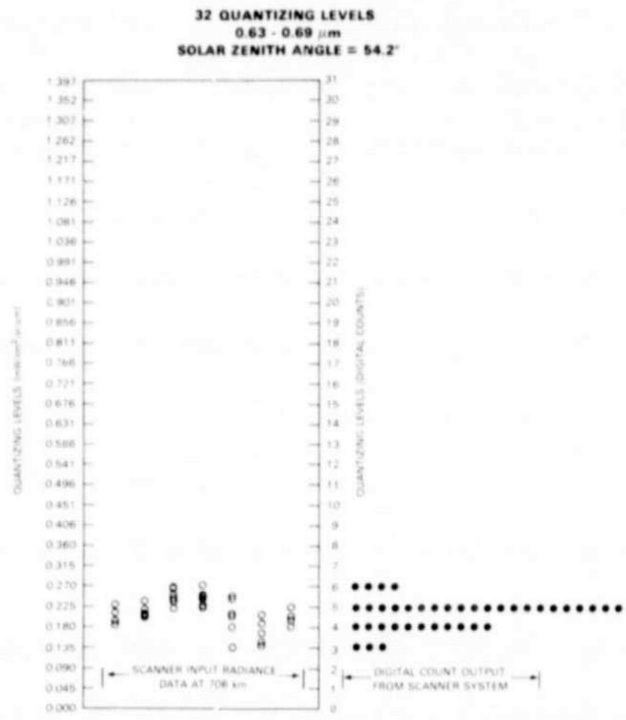


Figure 3. Radiance data at 706 km and associated linear combinations for the September 1971 grassland data. The reflectance data in Figure 2 were converted into radiance data by use of an atmospheric transfer model. (A) 0.63–0.69 μm radiance data, (B) 0.76–0.90 μm radiance data, (C) 0.76–0.90 μm/0.63–0.69 μm radiance ratio, and (D) the radiance normalized difference.



A



B

Figure 4. Conversion of TM3 (0.63-0.69 μm) radiance data at 706 km into digital count data for TM3 with 32 quantizing levels. (A) represents the radiance data presented to the satellite band, and (B) shows the quantizing levels (in energy units and the associated digital count values) and digital count output for the data in question.

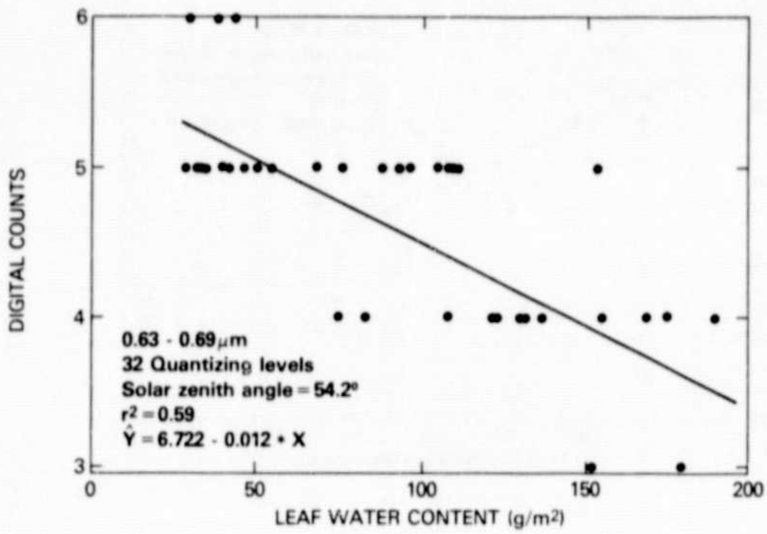


Figure 4 (Continued). Conversion of TM3 (0.63–0.69 μm) radiance data at 706 km into digital count data for TM3 with 32 quantizing levels. (C) plots the digital count output from (B) against the leaf water content. The degrading effect of quantizing at 32 levels is apparent by comparing (A) to (C).

was obvious that, depending upon the number of quantizing levels, a certain degree of "rounding-off" occurred. This was principally due to the number of quantizing levels but was also impacted by the solar zenith angle (Figure 5). Lower solar zenith angles were found to be limiting and thus were used to illustrate the quantizing levels results. In addition, there was a relationship between the solar zenith angle and the noise equivalent change in reflectance (NE$\Delta\rho$) (Figure 6).

The number of quantizing levels had a decided influence upon the relationship between the digital count and plant canopy biological data (Tables 3, 4, and 5). The 128 and 256 quantizing levels were consistently better in terms of r^2 values than 64 or lower quantizing levels. In a few cases, higher r^2 values were reported for some digital count variables than existed for the baseline reflectance data (i.e., TM3 for 34.62° and 64 levels). This resulted from "fortuitous" rounding-off and was an artifact of the analysis. Any departure from the baseline reflectance or radiance data

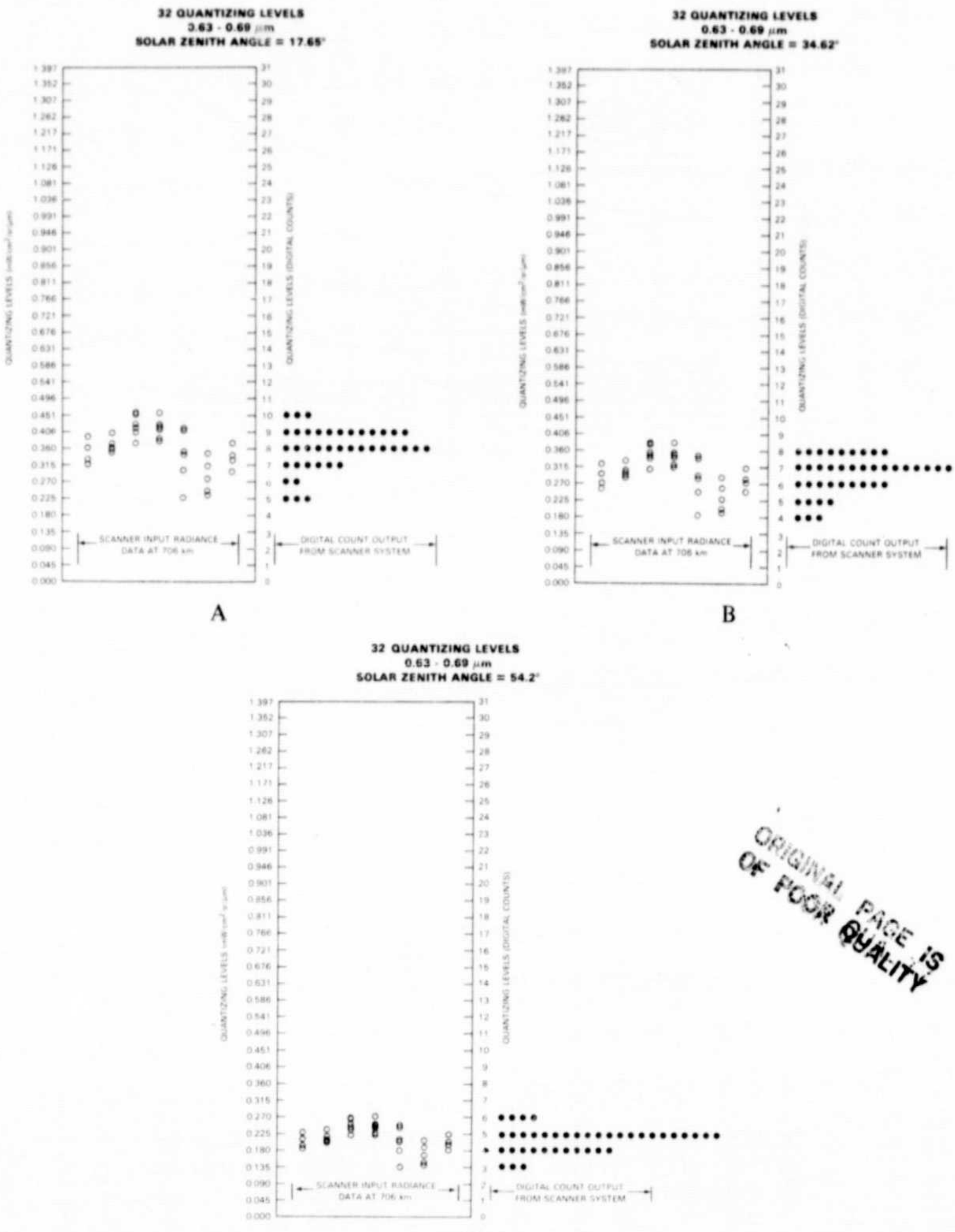
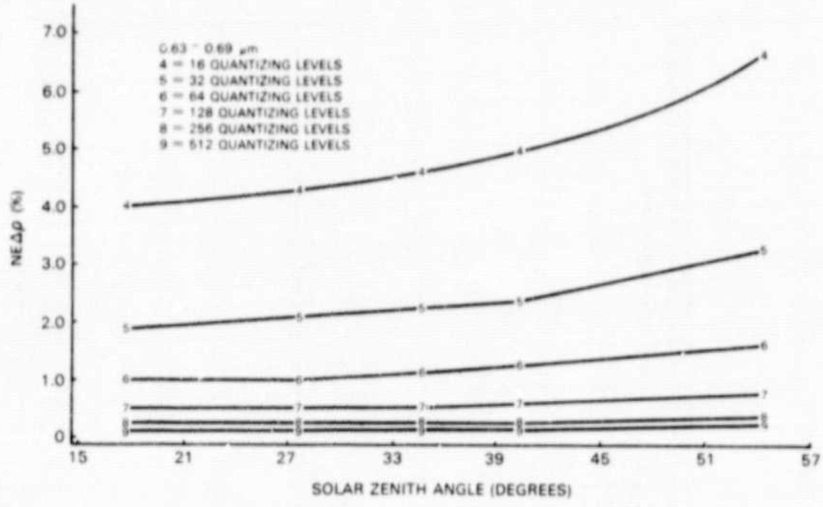
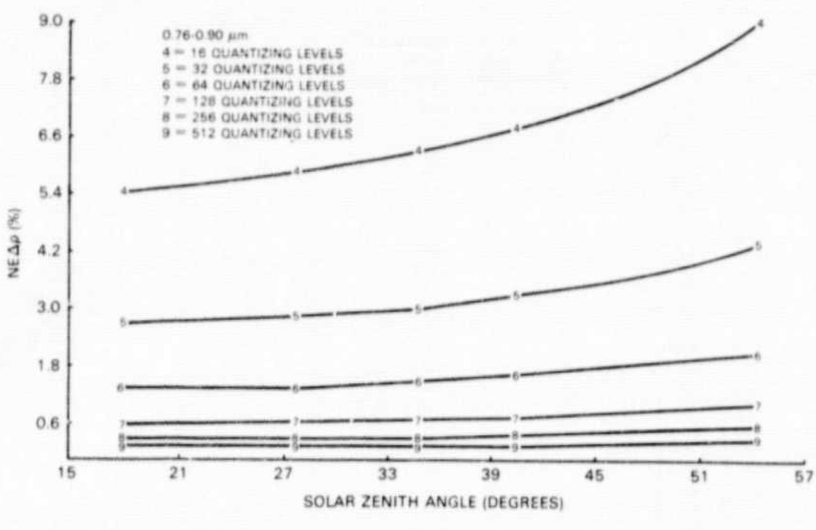


Figure 5. The influence of solar zenith angle upon digital count output range for TM3 (0.63-0.69 μm) with 32 quantizing levels. The same reflectance data is used with solar zenith angles of (A) 17.65°, (B) 34.62°, and (C) 54.2°. Note that (A) has 6 different digital count output values, and (B) has 5, and (C) 4.



A



B

Figure 6. The noise equivalent change in reflectance (NE$\Delta\rho$) for (A) TM3 and (B) TM4 as a function of solar zenith angle and number of quantizing levels for a clear rural atmosphere.

was considered as an expression of a degrading influence in the analysis. This was in every case confirmed by referring to the plotted data of the fortuitous rounding-off.

It was apparent from the analysis that 128 levels were approximately 2% superior in a regression sense to 64 levels. Sixteen and 32 quantizing levels were dismissed from consideration because of their demonstrated regression inferiority (Tables 2, 3, and 4). No systematic regression improvements were found for 512 levels vs. 256 levels. This suggested that 256 levels represented the maximum number of quantizing levels required for orbital remote sensing of vegetation resources using satellite sensor bands similar to Thematic Mapper bands TM3 and TM4.

In order to eliminate the possibility that the *in situ* reflectance data had "biased" the analysis, the analysis was rerun for a data set of perfectly correlated data. This was accomplished by using the regression equations in Figures 2a and 2b to generate perfectly correlated reflectances with respect to the leaf water content. These data were solar irradiated and passed upwards by the identical atmospheric model to 706 km where they were quantized at 16, 32, 64, 128, 256, and 512 levels for TM3 and TM4 bands. The simulated digital counts were subsequently regressed against the leaf water content (Table 5).

The results of the perfectly correlated radiance data analysis agreed closely with the *in situ* reflectance results. A 2% improvement resulted from quantizing at 128 vs. 64 levels for both TM3 and TM4 (Figure 9). A 1% improvement resulted from quantizing at 256 vs. 128 levels for TM3 and TM4. A 2% improvement resulted for the TM4/TM3 digital count ratio for 128 vs. 64 levels with no improvement for 256 vs. 128 levels for this same ratio of Thematic Mapper bands (Table 5). A 1% improvement resulted for the normalized differences for 128 vs. 64 levels and a 1% improvement existed for 256 vs. 128 levels.

The results of the perfectly correlated data analysis suggested that the *in situ* reflectance data analysis was valid and furthermore demonstrated the ~2-3% improvement per channel resulting

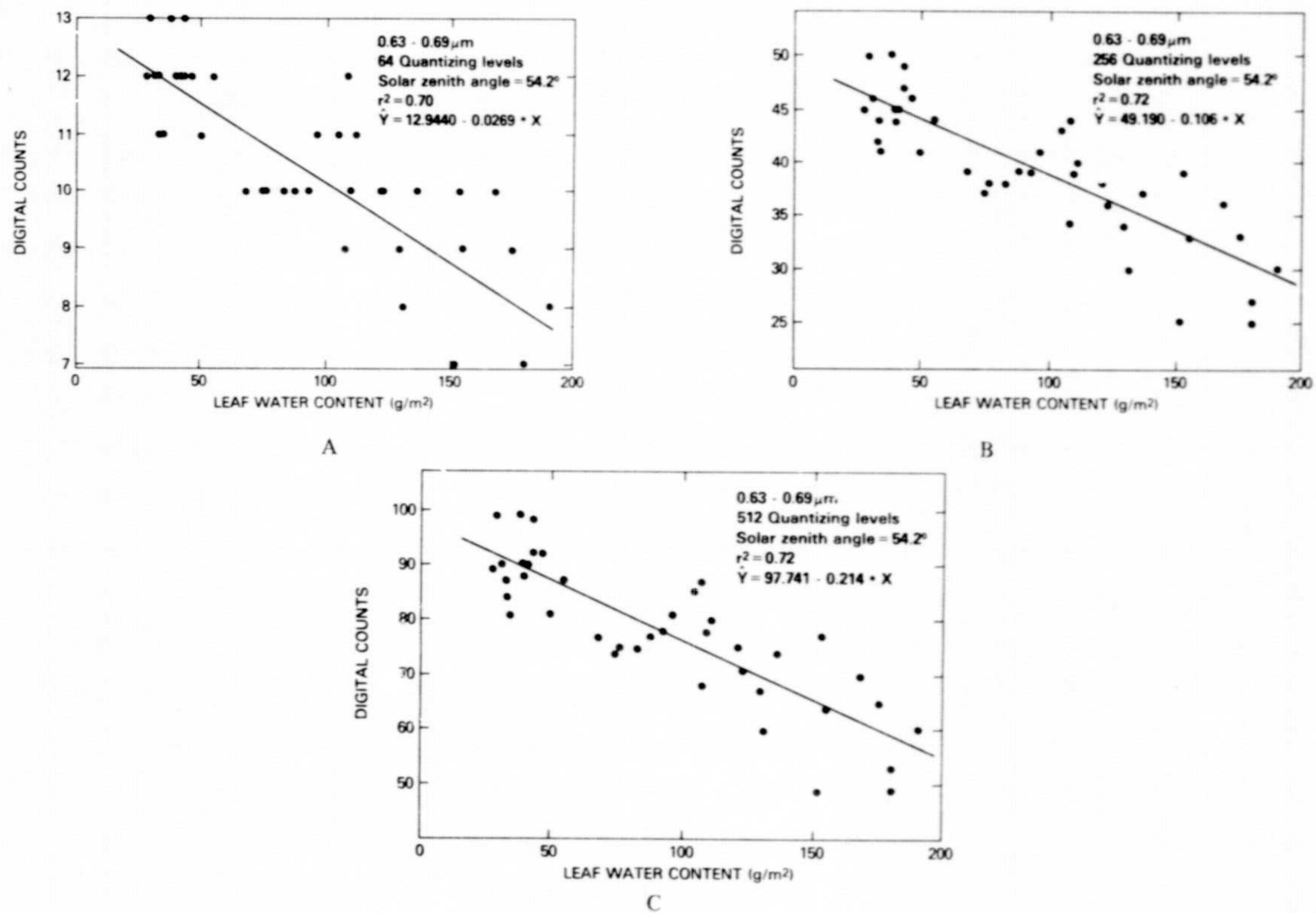


Figure 7. TM3 digital count output plotted against the leaf water content for the September, 1971 data for (A) 64 quantizing levels, (B) 256 quantizing levels, and (C) 512 quantizing levels. Note the 2% improvement between 64 and 256 quantizing levels.

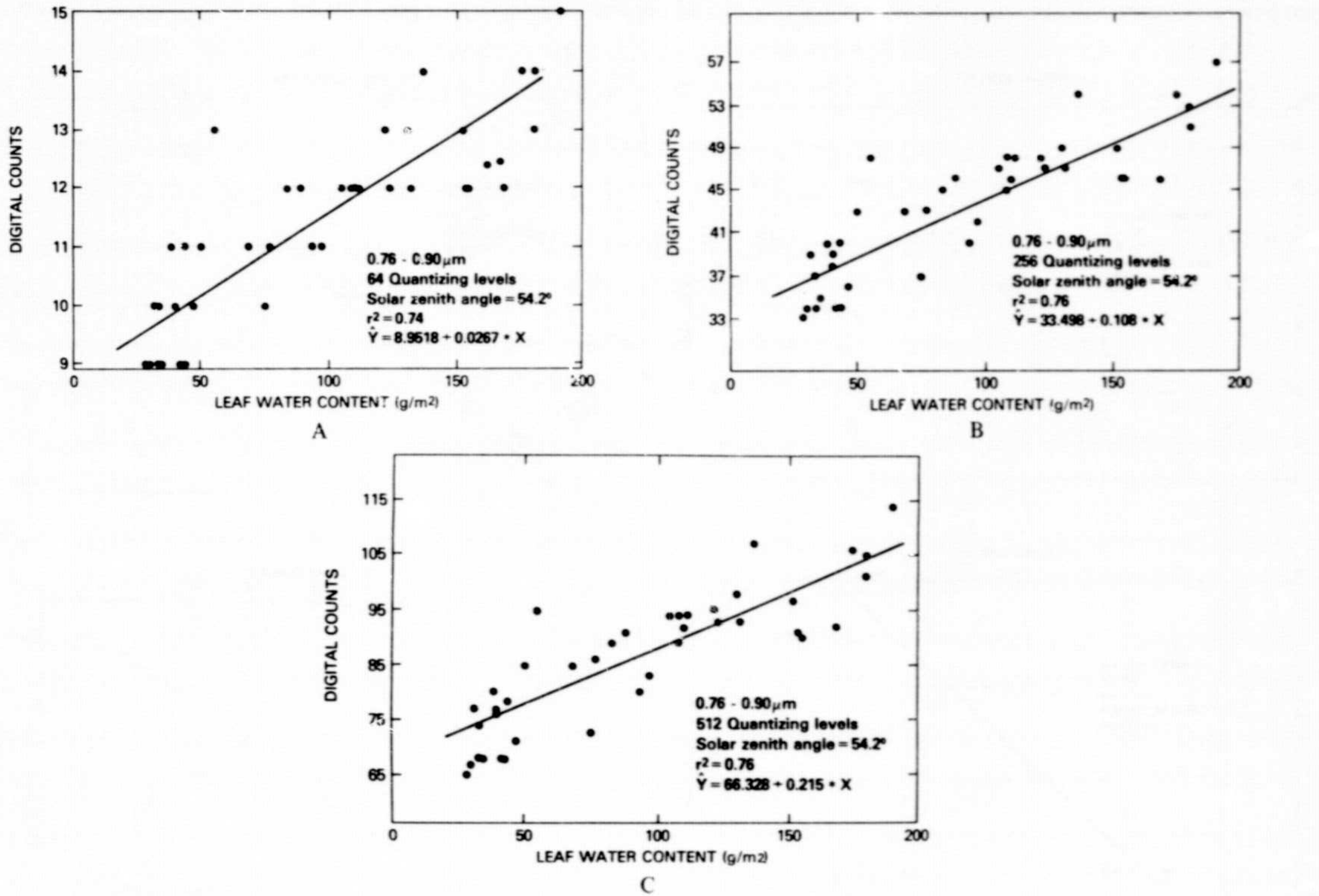


Figure 8. TM4 digital count output plotted against the leaf water content for the September, 1971 data for (A) 64 quantizing levels, (B) 256 quantizing levels, and (C) 512 quantizing levels. Note the 2% improvement between 64 and 256 quantizing levels.

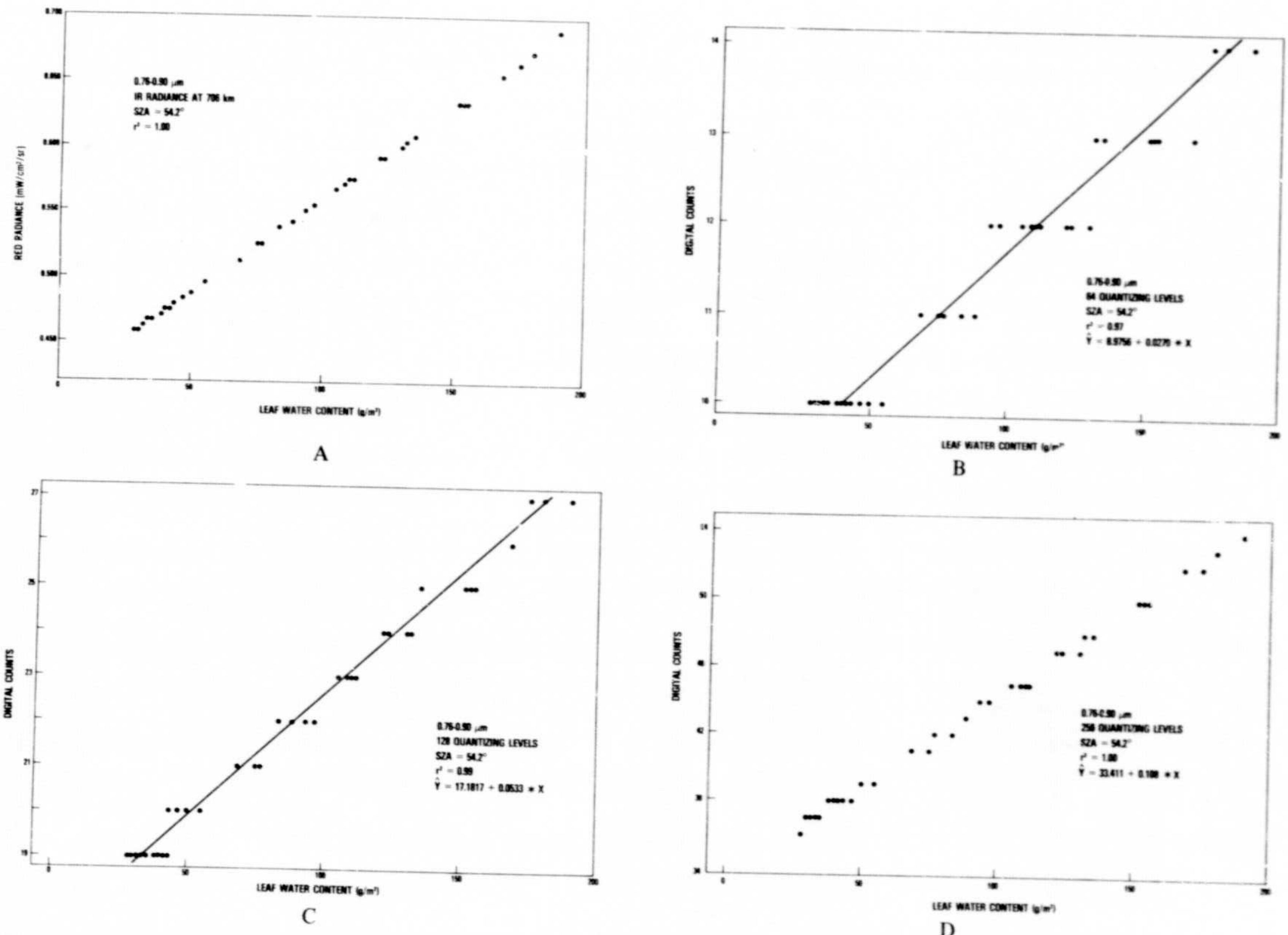


Figure 9. Perfectly correlated data for TM4 for (A) radiance data at 706 km, (B) 64 quantizing levels, (C) 128 quantizing levels, and (D) 256 quantizing levels. The reflectance data used to compute the TM4 radiances was generated by the regression equation in Figure 2b. Similar regression results were found for TM3. See also Table 5.

from 256 quantizing levels vs. 64 for sensors similar to Thematic Mapper bands TM3 and TM4. It is extremely doubtful if more than 256 quantizing levels would ever be practical for orbital resource missions and 128 quantizing levels could well be adequate. In addition, the results of this study agreed with the previously referenced study of a very different nature by Morgenstern et al. (1976) (Table 6). General comparisons between these two studies were favorable. The results of Morgenstern et al. (1976), however, showed that an improvement in simulated classification accuracy resulted in five out of seven cases for a NE$\Delta\rho$ of 1.0% vs. 0.5% (Table 6)*. This could have resulted from the actual scanner system NE$\Delta\rho$ being ~ 1.0% for the data sets used by Morgenstern et al. (1976).

The MSS of Landsats-1, 2, and 3 quantizes input radiances into 64 levels. Landsat-D's Thematic Mapper will quantize input radiances into 256 levels. The data presented in Tables 2, 3, 4, and 5 demonstrate that a radiometric resolution improvement of 1-4% (average of ~2-3%) per channel resulted from quantizing at 256 levels vis-a-vis 64 levels for TM3 and TM4. This is a small but

TABLE 6
Simulated Classification Results of Morgenstern et al. (1976) as a Function of Radiometric Sensitivity. Note the 1 to 10Classification Percent Improvement of 0.5% vs. 2.0% NE$\Delta\rho$.

Study Segment	IFOV = 30 m			IFOV = 40 m		
	Noise Equivalent Change in Reflectance (NE$\Delta\rho$)*					
	0.5%	1.0%	2.0%	0.5%	1.0%	2.0%
S-204, 43M	96.6	97.7	95.3	98.0	98.4	96.2
S-204, 42M	96.9	97.1	96.1	95.5	97.3	96.1
S-204, 41M	86.9	88.9	82.1	92.3	91.2	84.9
S-212, 43M	NA	NA	NA	91.2	90.1	81.4

*0.5% = ~256 levels; 1.0% = ~128 levels; and 2.0% = ~64 levels.

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*NE$\Delta\rho$ of 1.0% = ~128 level; NE$\Delta\rho$ of 0.5% = ~256 levels.

substantial improvement over the MSS. When coupled with spectral resolution improvements (better TM band selection), an increased number of bands, and spatial resolution improvements (30m IFOV), additional improvements are expected from the interaction(s) of these three "resolution" parameters.

CONCLUSIONS

1. The solar zenith angle was found to have an influence upon the noise equivalent change in reflectance.
2. Quantizing levels had a decided effect upon the ability to resolve spectral radiances which were highly related to plant canopy vegetational status.
3. TM3 and TM4 showed a per channel improvement of 2-3% for 256 levels vs. 64 levels. A slight (approximately 1%) improvement resulted from 256 levels vs. 128 levels. No improvements were found for 512 vs. 256 levels.
4. The TM4/TM3 ratio and the normalized difference showed a 1-3% improvement for 256 levels vs. 64 levels. No improvement(s) were found for 256 levels vs. 128 levels for these linear combinations.
5. Either 128 or 256 quantizing levels appear optimum for orbital monitoring of terrestrial vegetation for TM3 and TM4 bands or similar sensor bands.
6. The radiometric resolution of the Thematic Mapper was found to be closely matched to the scene dynamic radiance range for vegetated targets without incorporating variable gain control in the instrument.

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