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THEMATIC MAPPER RADIOMETRIC CHARACTERIZATION

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I. ABSTRACT

Characteristics of multispectral scanner systems that are desirable for radiometry are identified. Both "macroscopic" and "microscopic" studies of Landsat-4 Thematic Mapper digital image data are described which assess several of these characteristics. Included are the range and quantization of signal values, scan-angle effects, scan-direction effects, and level-shift noise characteristics. Despite good overall radiometric quality, some relatively low-amplitude artifacts were noted and correction procedures are recommended. Consideration of the use of stepwise linear system-response characteristics is recommended. The acquisition of a unique data set of coincident Landsat-4 and Landsat-5 data is noted; it was acquired before Landsat 5 reached its final orbit.

II. INTRODUCTION

Multispectral remote sensing systems, such as the satellite-borne Landsat Multispectral Scanner (MSS) and Thematic Mapper (TM) systems, provide capabilities for monitoring Earth resources. The geometric and radiometric characteristics of image data from such sensors affect their utility for various applications. NASA established a Landsat Image Data Quality Analysis (LIDQA) Program, involving several government and non-government investigators, to conduct engineering studies of early Thematic Mapper Data [1]. The work described here is a part of that effort [2,3]. The Landsat-4 system was launched in July 1982 and the Landsat-5 system in March 1984.

This paper addresses elements of the radiometric characterization of Landsat Thematic Mapper image data. An understanding of sensor radiometric characteristics is desirable so that sensor-related image features will not be erroneously interpreted as being associated with scene phenomena. It also can help permit valid intercomparisons of responses from different satellite systems.

Table I lists desirable characteristics of a multispectral scanner system that are important for radiometry. We here will address several of them in relation to data from the Landsat-4 Thematic Mapper system. Since Landsat-5 had only recently been launched at the time of this writing, the oral presentation will include a status report on the Landsat-5 TM at the time of the symposium.

III. APPROACH

The approach we have taken in analyzing TM radiometry involves both macroscopic and microscopic analyses of digital computer-compatible-tape (CCT) image data from several scenes. These data were obtained at several different stages of ground data processing in order to examine the results of each stage and assess their effectiveness.

The macroscopic analyses were designed to assess trends within spectral bands over the full 185x185-km frames of data. First, histograms and statistical measures (e.g., means and standard deviations) of signal amplitudes were computed for each band. Where available, radiometrically corrected and fully corrected data were examined and compared. Selected scatterplots were made of data in pairs of bands and signal correlations computed.

Second, average scan lines (amplitude vs. pixel number of scan angle) were computed, one for each band, by averaging down track over the entire frame at constant pixel locations. Third, to explore the other image dimension, down-track profiles (amplitude vs. scan line number) were computed, one for each band, by averaging all pixels (or a systematic sample) on each line to obtain a single average value for each scan line. Fourth, to study any scan direction effects in TM, average scan lines were computed for each band, separately for each of the two scan directions. Computer plots and listings of the computed average scan lines and down-track profiles were produced and analyzed.

The microscopic analyses were designed to assess differences between individual detector responses before and/or after equalization within each spectral band (16 for each reflective band and four for the thermal band). They also were designed to examine noise characteristics by detector, both down-track and along the scan line. Many of the analyses conducted on spectral band values were repeated for each individual detector to provide data for comparison. Detector histograms and related statistics, together with the down-track profiles, permitted assessment of the ground system's success in equalizing detector responses. A unique aspect was our analysis of nighttime TM data from the reflective channels. Fourier analysis of down-track profiles also was used to assess the success of equalization and to detect the presence of periodic banding and striping effects. A Fast Fourier Transform (FFT) technique adapted from Reference 4 was used.

IV. DATA SET

Table II identifies the frames of TM data which have been analyzed to date. They were acquired during the first six months of Landsat-4 operation. Raw data (CCT-BT) and radiometrically corrected data (CCT-AT) were the primary inputs for our studies, with added analyses of fully (geometrically as well as radiometrically) corrected data (CCT-PT) and calibration data (CCT-ADDS). The CCT-BT and CCT-ADDS are special engineering products not generally available to users.

After the launch of Landsat-5 on 1 March 1984, a period of system checkout and orbit adjustment began, with full system operation scheduled for early April 1984. During 14-16 March 1984, as the Landsat-5 system was moving toward its final orbit, passes within the U.S. were covered nearly simultaneously by the Landsat-4 and Landsat-5 systems. This data set will provide a unique opportunity for direct comparison of the radiometry of these two systems since, from April, on their 16-day coverage cycles will be spaced eight days apart.

V. TM DATA ANALYSIS RESULTS

A. GENERAL CHARACTERISTICS

Signal Histograms and Dynamic Range: Signal values over the full 0-255 signal range were observed in all six reflective bands, with clouds frequently causing saturation. However, in a cloud-free, primarily agricultural scene (Iowa), we found narrow concentrations of signals in all bands but TM4 and TM5 which have somewhat broader distributions.

The TM4 signal histograms in Figure 1 illustrate other TM characteristics. In Parts (a), (b) and (c), responses from all detectors are grouped together. A ragged histogram shape is evident for the raw data of Part (a), the results of unequal step sizes in the analog-to-digital converter of the sensor. After radiometric correction, Part (b), the levels of individual detectors are shifted with respect to each other and the raggedness is decreased. Finally, the cubic-convolution interpolation process used in geometric correction results in a smooth histogram, Part (c), for the fully corrected data. Parts (d) and (e) are for a single detector, with Part (d) again displaying step size variation of the analog to digital converter. When the radiometric correction process involves a stretching of the signal range (gain > 1.0), occasional gaps (empty levels) are created in the histograms as a direct result of the quantized, integer nature of the signal values, as shown in Part (e). Because the detectors have slightly different gains and offsets, these empty levels are not evident in the histogram for the entire band, Part (b), although they will still be present for individual detectors in CCT-AT data.

Detector Equalization and Down-Track Profiles: Detector equalization within TM bands was found to be close to the theoretical limit of quantization. Residual differences in CCT-AT detector means were evident in corresponding CCT-PT scan-line means (down-track profiles) and in imagery.

In addition to the residual differences in detector means, we discovered another down-track artifact: very low frequency, scan-related noise in the form of level shifts that occurred in the mean values of individual detector means [2,3]. Other investigators also reported related observations [e.g., 5].

Scan-Angle Effects: Upon examination of plots of average scan lines (amplitude vs. scan angle (pixel number)), it was found that values near the Western edge of the scene were substantially higher than those near the Eastern edge, as shown in Figure 2. The effect, more pronounced in the short wavelength and thermal bands, can be attributed to sun-view geometry and combination of atmospheric, bidirectional- reflectance and shadowing effects. Previous modeling work has predicted atmospheric scan angle effects similar to those observed here [e.g., 6,7]. Atmospheric effects are greatest in Band TM1 and atmospheric effects are reduced as the wavelength increases and bidirectonal reflectance effects become the drivers of observed trends. Shading and view direction contribute to the observed thermal responses.

In addition to the expected scene-related scan-angle effects described above, we discovered a sensor-related scan-angle effect that is associated with the direction of mirror scan.

B. SCAN-DIRECTION ARTIFACT AND CORRECTION MODEL

Description of Artifact: From plots of average scan lines for the two scan directions, we found a slight but consistent anomaly, the difference between West and East edge values was greater for forward (W-E) scans than for reverse (E-W) scans. Figure 3 illustrates the results for Bands TM1 and TM6 for the Iowa frame, but it was observed in other bands as well. The previously described scan-angle effect is still dominant, but it appears that a systematic droop of signal values occurs during the active scan. This tends to increase the overall scan-angle effect for forward scans and reduce it for reverse scans for the reflective bands, being most pronounced in TM1. Thus, 16-detector-wide swaths (approximately 17 lines on CCT-PT tapes and images) can differ from neighboring swaths by opposite amounts at the two frame edges, while little if any of this effect will be present at frame center.

In the thermal band, TM6, the swaths are four detectors wide and, as seen in Figure 3, the scan-direction artifact for the September 1982 scene was markedly different from that of Band TM1 and the other reflective bands. This unique thermal band artifact has been observed in other scenes and and by other investigators [8].

Correction Model: In order to characterize the scan-direction effect, the ratio of forward-scan signal level to reverse-scan signal level was computed as a function of scan angle (pixel number). Then, to produce a preliminary model of the effect, the data were fit to an exponential decay model [2,3]. With this model, the predicted decay began prior to the first pixel, having decayed approximately 1% by that time. The total decaying approximately 2.25% by the end of the active scan. This results in the mean signal level of the forward scan being approximately 0.75 counts higher than the mean signal level of the reverse scan at the West edge of the scene, and approximately 0.75 counts lower at the East edge of the scene for Band TM1 (Scene 40049-16262). The best fit occurred when the exponential decay began at the time of DC restore (different times for the two scan directions). During DC restore, a dark (no radiance) level is presented to the detectors, and a DC level capacitor is charged to a value which results in approximately two signal counts. This charge was designed to be held for the entire scan, having a time constant on the order of minutes [9]. The empirically derived scan-direction effect model suggests that this charge may be decaying much faster (time constant of the order of 10 msec).

We plan to continue our investigation of this effect, refine the preliminary correction model, and extend the analysis to other bands.

C. LEVEL-SHIFT ARTIFACT AND RECOMMENDED CORRECTION PROCEDURE

Description of Artifact: When down-track profiles (mean signal vs. scan-line number) for individual detectors (every 16th line) from CCT-BT and CCT-AT data were examined, two patterns of level shifts were observed as one progressed down the frame. All detectors exhibited to some degree these step changes in mean signal across entire scan lines, although for most detectors the magnitude of the level shift was <0.5 signal count. Also, it was found that these level shifts were correlated among detectors. Each detector exists in one of four noise states representing the combinations of the two forms or patterns of level shift and their respective phases.

Form #1 of the level-shift artifact is exemplified by the first band, as illustrated in Figure 4. TM1 Detectors 4, 12, 10 and 8 showed the greatest effect, with level shifts of 2.2, 1.8, 1.0 and 0.75 signal counts, respectively, occurring at random and usually having several to many scans at a given level before shifting to the other level. A very noise-free definition of this pattern was obtained through analysis of nighttime frames of data from the reflective-band detectors. More than 6,000 pixels were averaged to obtain each scan-line average value shown in Figure 5.

The pattern of the second form of level shifts is exemplified by Detector 7 of TM7, as shown in Figure 6, again from nighttime data. This Form #2 noise pattern is characterized by much more regular and frequent level shifts than Form #1, often two mirror sweeps in each state.

While we have observed the Form #2 level-shift noise patterns in all of the frames we have analyzed, the Form #1 pattern was absent in the most recent scene we examined (Grand Bahamas) and a portion (∿1/3) of the earlier Augusta night scene (Figure 5). Nevertheless, level-shift artifacts have occurred sufficiently often to warrant development of a correction procedure. For example, level shifts of the magnitudes observed in TM1 could seriously interfere with quantitative applications of TM data, such as in bathymetry [10]. Although we have not identified the specific noise sources in the sensor, we believe we have characterized the level-shift artifacts sufficiently to develop empirical methods for substantially reducing their effects in scene data.

Recommended Correction Procedure: A correction procedure requires a diagnostic measurement to determine the level-shift noise state of each detector on each scan line, in addition to a method for applying the corrections. Several alternatives for a diagnostic measure were examined. The most promising uses data values obtained when the calibration shutter is blocking the input radiation and no calibration lamps are in the field-of-view. We obtained several CCT-ADDS tapes from NASA/GSFC. These tapes contain the desired samples of dark calibration shutter data in two data windows, each 24 or 28 pixels in width. We averaged the samples in the window that followed the DC-restore procedure for each detector for each scan line. The resulting down-track profiles again reproduced the level-shift pattern observed in scene data. Upon comparing the calibration shutter profiles for TM1 with the corresponding profiles from scene data and nighttime data we found that while they exhibited more random noise than the nighttime data (24 samples averaged vs. 6,000), they did not exhibit the scene-dependent fluctuations evident in the scene data. In addition to serving as a diagnostic of the system noise state, the dark calibration shutter values also give an estimate of the level shift magnitudes.

Therefore, the correction procedure we recommend would compute the average of observations of the dark calibration shutter, after DC restore, and subtract the corresponding value from each pixel value on the scan line for the particular detector. Since this subtractive value will mostly likely be non-integer, incorporation of this offset would best be accomplished in the computation of the Radiometric Look-Up Table (RLUT), so as to eliminate an additional rounding/ truncation step. This would, however, require an update of that table for each mirror sweep (every 16 scan lines).

D. OTHER ASPECTS OF RADIOMETRY

Various LIDQA investigators are considering other aspects of radiometry as well, such as listed in Table I, but we will not attempt to summarize them here. The reader is instead referred to Reference 1 and related publications.

One matter which is of concern to applications with far different objectives is the establishment of signal-response vs. radiance input characteristics. Investigators dealing with snow, clouds and other bright scene materials do not want signal saturation to occur and are less concerned about a high degree of radiance responsivity than are investigators dealing with low reflectance scene materials. We have recommended consideration be given to use of non-linear or stepwise-linear response characteristics that could provide small radiance steps (small radiance intervals for each digital count) for low-radiance targets, moderate radiance steps for average targets, and larger radiance steps for high-radiance targets [11]. While complicating the ground processing and data interpretation somewhat, this approach might serve as a good compromise between conflicting user needs.

Also, we note that the needs of users of film image products may differ from those of digital data users. For instance, a film user may be willing to slightly increase radom noise (as measured by a statistical parameter such as variance) if it provides an image product that has reduced visual effects of pattern noises such as striping or banding [12].

VI. SUMMARY

Desirable system characteristics for multispectral scanner radiometry were identified. Based on engineering analyses directed at assessing several of these characteristics, Landsat-4 Thematic Mapper data were found to have an overall good radiometric data quality, in addition to their very good spatial resolution. Radiometric equalization of detectors was found to be close to the theoretical limit of quantization error, except for two relatively low-amplitude artifacts. The first was a scan-direction artifact caused by signal droop during the active portions of each forward and reverse scan. This artifact was most pronounced in TM1 of the reflective bands, while the thermal band (TM6) had a unique pattern. The second artifact was a low-frequency scan-related level shift which occurred in two forms, leading to four system noise states. Again, this artifact was most evident in TM1. Initial correction procedures have been developed and recommended for further evaluation. The presence of scan-angle effects due to atmosphere characteristics and scene bidrectional-reflectance effects was noted and it is suggested that attention be directed toward development of normalization procedures. We have identified a possible solution to conflicting user needs relative to the system response characteristic (digital counts vs. radiance input). After the successful launch of Landsat 5, several passes of near-simultaneous data were acquired with it and Landsat 4; this will provide a useful data set for future analysis.

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TABLE I. DESIRABLE SYSTEM CHARACTERISTICS FOR MULTISPECTRAL SCANNER RADIOMETRY

Within each spectral band, the following are desirable:

1. Uniformity of spectral responses among detectors.
2. Consistent and known detector radiance-response characteristics and equality among detectors.
3. Adequate sensitivity and range of signal amplitudes for varied appli- cations.
4. Similarity of noise characteristics among detectors and overall low noise levels.
5. Analog-to-digital conversion of signal amplitudes that is consistent and matched to system range and noise characteristics.
6. Absence of systematic noise effects.
7. Uniform response vs. scan angle.
8. Uniform response vs. scan direction.
9. Fast detector response, with minimal overshoot or smearing, at sharp discontinuities in scene radiance patterns.
10. Constant-with-time radiance cali- bration of output signals and/or knowledge of calibration changes (i.e., accurate relative calibration).
11. Independence of satellite system, when part of a sequence of sensors.
12. Absolute radiance-responsivity calibration, with specified error bounds.
13. Consistent and well documented ground processing procedures.
14. Appropriate substitution of values from dead or faulty detectors.
15. Minimum degradation of spatial and radiometric integrity of data during any resampling as a part of geometric correction.
16. Requisite calibration information in digital tape headers.

TABLE II. TM ANALYSIS DATA SET

Geographic Location	Path/Row	Date	Frame Number	Scene Type
Arkansas	23/35	22 Aug 82	40037-16034	Agriculture, some clouds, water
Iowa	27/30	3 Sep 82	40049-16262	Agriculture, clear skies
North Carolina	14/36	24 Sep 82	40070-15084	Agriculture, much cloud, water
Cape Cod	11/31	8 Dec 82	40145-14492	Low radiance, clouds much water
Georgia	116/207	24 Dec 82	40161-02481	Nighttime
Grand Bahamas	14/42	14 Jan 83	40182-15125	Water, clouds

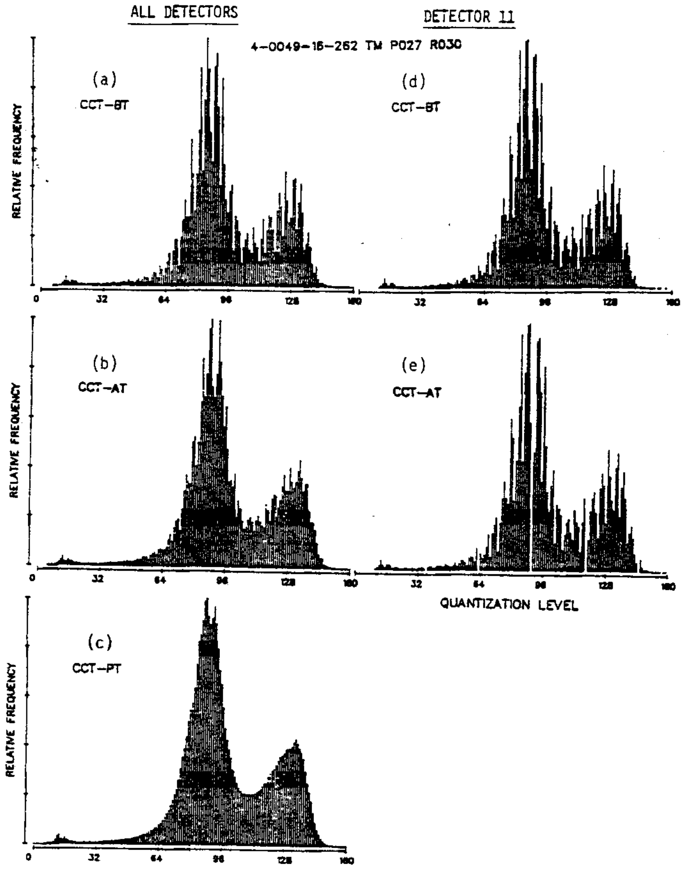

Figure 1. Quantization - Level Histograms
Thematic Mapper Band 4

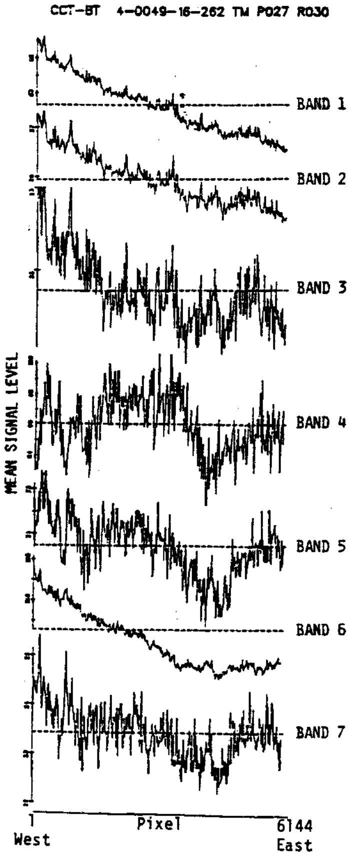

Figure 2. Scan-Angle Effect

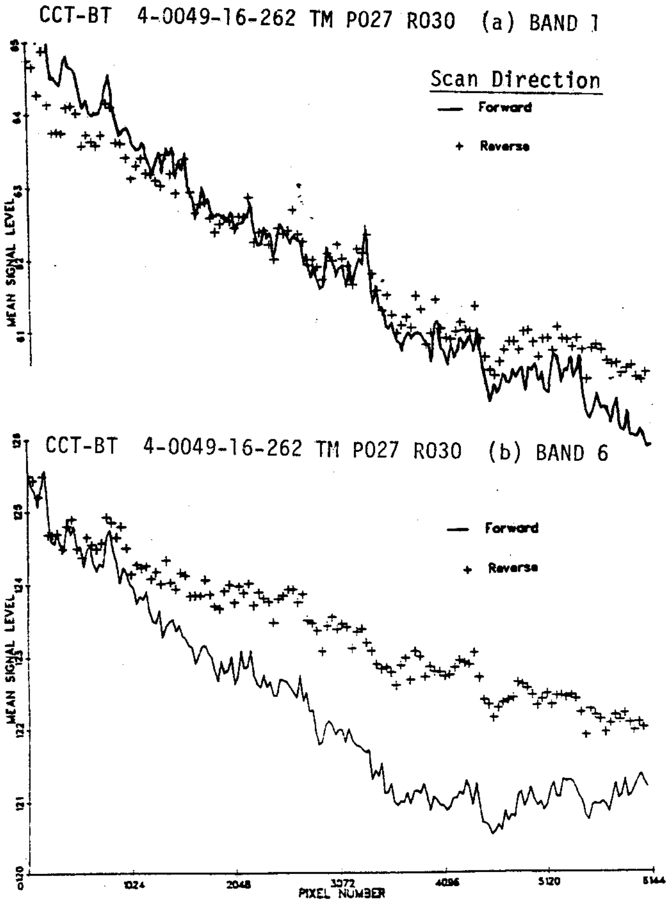

Figure 3. Scan-Direction Effect

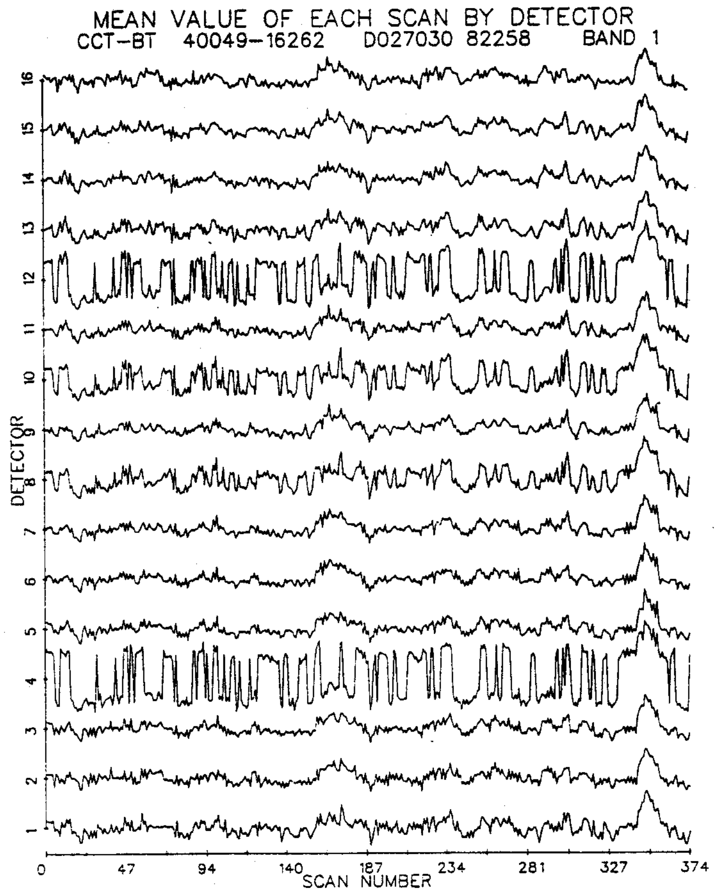

Figure 4. Down-Track Profiles: Scan Averages of Scene Data, Before Correction, Band TM1

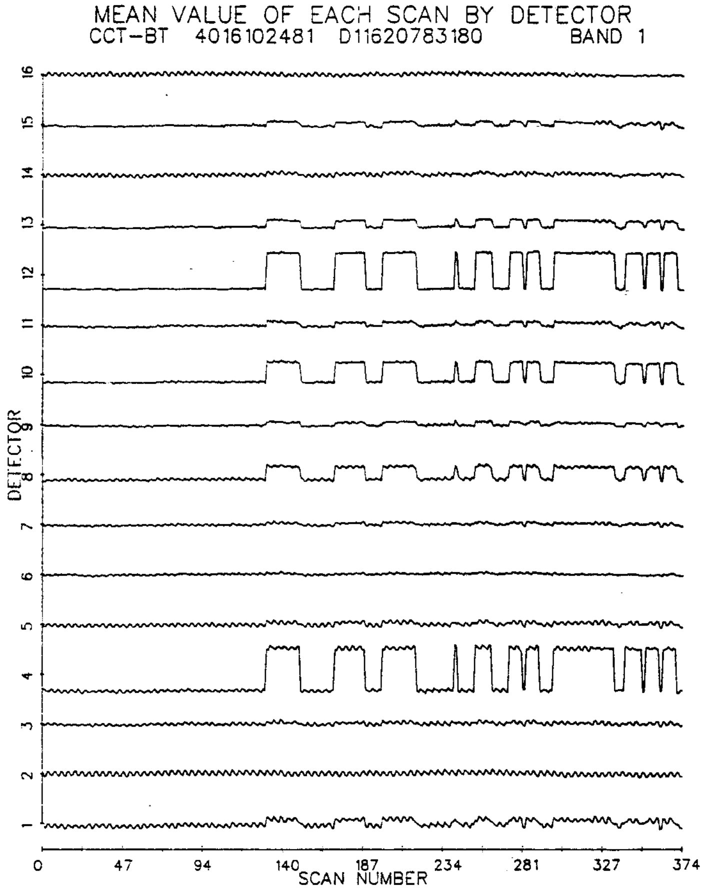

Figure 5. Scan Averages (By Detector) of Nighttime Scene Data, Band TM1

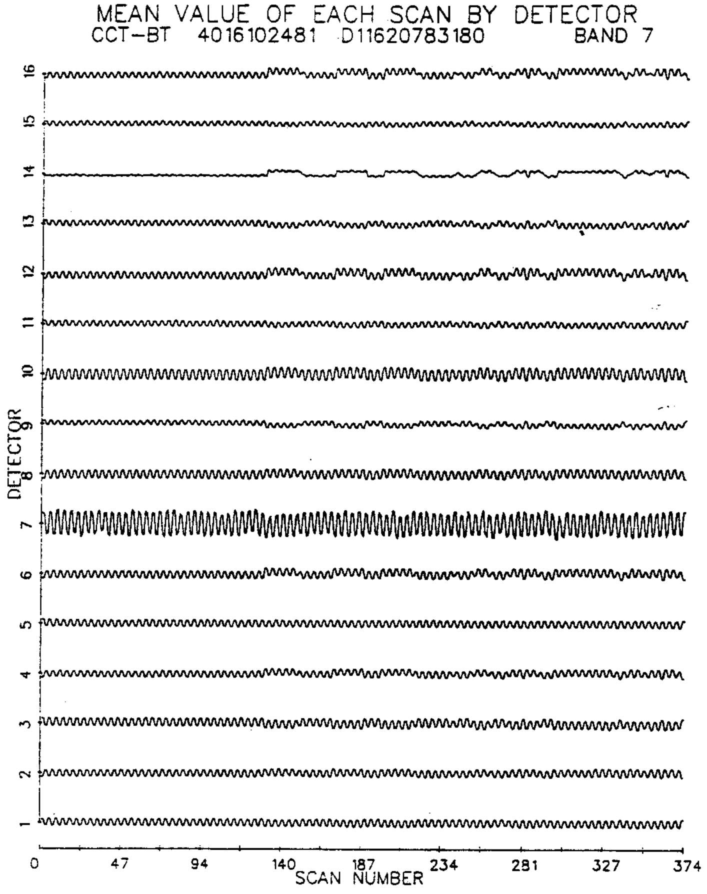

Figure 6. Scan Averages (By Detector) of Nighttime Scene Data, Band TM7

AUTHOR BIOGRAPHICAL DATA

William A. Malila received B.S. and M.S. degrees in Electrical Engineering from Michigan State University and Stanford University in 1956 and 1960, respectively. His Ph.D. degree in Forestry, with a remote sensing concentration, was received from the University of Michigan in 1974.

Since 1960 when he joined the technical staff of ERIM (then the Willow Run Laboratories of the U of M), he has been active in the development and testing of techniques for extracting information from remotely sensed data, especially multispectral scanner data, and the use of models and system analysis for better understanding phenomenology and interactions. He has participated in technical research and management of NASA-sponsored supporting research activities for projects such as LACIE and AgRISTARS, and has been an Investigator on Landsat and Skylab investigations.

Michael D. Metzler was born in Nappanee, Indiana. He received his B.S. and M.S. in physics from Manchester College and Michigan State University, respectively. Prior to joining the Environmental Research Institute of Michigan (ERIM) in 1980, he was employed as a systems programmer, first by IBM's Federal Systems Division and then by Burroughs Corp. He has been active in several areas of civilian remote sensing, ranging from development and implementation of agricultural remote sensing procedures to engineering analyses of sensor systems and thermal modeling.