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Final Report

INVESTIGATION OF RADIOMETRIC PROPERTIES OF THE LANDSAT-4 MULTISPECTRAL SCANNER

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$$b = \begin{matrix} 1.114 \\ 0.000 \\ 1\ 008 \\ 0.651 \end{matrix}$$

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16. Abstract

The radiometric data quality of the Landsat 4 multispectral scanner (MSS) was examined using several Landsat 4 frames. It was found that Landsat 4 MSS produces high-quality data of the calibre experienced with previous Landsats. For example, the detector equalization procedure worked well, leaving a residual banding effect of about 0.3 digital counts RMS, close to the theoretical minimum value of quantization error.

Nevertheless, artifacts of the data were found, two of which were not experienced in previous MSS data. A low-level coherent noise effect was observed in all bands, with a magnitude of about 0.5 digital counts and a frequency of approximately 28 KHz (representing a wavelength of about 3.6 pixels); a substantial increase in processing complexity would be required to reduce this artifact in the data. Also, a substantial scan-length variation (of up to six pixels) was noted in MSS data when the TM sensor was operating; the Landsat 4 correction algorithms being applied routinely by the EROS Data Center to produce to "P"-type data should remove most of this variation.

Between-satellite calibrations were examined in paired Landsat 3 and Landsat 4 MSS data sets, which were closely matched in acquisition time and place. Radiometric comparisons showed that all bands were highly linear in digital counts, and a well-determined linear transformation between the MSS's was established. A similar relationship was established between Landsats 2 and 4 using less data.

Geometric fidelity of "A"-type data between one Landsat 3/Landsat 4 pair of frames, after correcting Landsat 4 data for line-length variation, was 1.8 pixels across track, and 0.8 pixels down track. The expected-to-be-smaller errors between "P"-type frames were not measured.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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Foreword

This investigation is one of several sponsored by the National Aeronautics and Space Administration (NASA) as part of the Landsat-4 Image Data Quality Analysis Program, and was identified as AN-23, Study on Radiometric Consistency of Landsat-D Multispectral Scanner. It was administered by the Goddard Space Flight Center, with Mr. Harold Oseroff, Code 902, serving as Technical Officer and Mr. Ross Nelson, Code 923, serving as Science Representative.

The research was conducted by the Environmental Research Institute of Michigan (ERIM) within its Infrared and Optics Division, headed by Dr. Jack Walker, and Information Processing Department, headed by Mr. Robert Horvath. Dr. William A. Malila was Principal Investigator and Mr. Daniel P. Rice was Co-Investigator.

The authors wish to acknowledge Mr. Howard W. Warriner of NOAA's EROS Data Center, Sioux Falls, SD, for assistance in acquiring data sets, Mr. Thomas Wessling of ERIM for technical support, Mr. Thomas Parris for contributions to Appendix A, and Ms. Patricia Wessling and Miss Darlene Dickerson for secretarial support.

1
INTRODUCTION

1.1 BACKGROUND

The Landsat user community has been concerned about the continuity of Landsat multispectral scanner (MSS) data. Landsat-4 extends the decade of data availability afforded by the first three Landsat satellites. We believe that continuity should be thought of not only as being the continued availability of high quality Landsat MSS data, but also the consistent interpretability of signal amplitudes and spectral features extracted from MSS data. Hence, of interest are both the internal calibration between detectors within each spectral band, with related dynamic-range and signal-to-noise characteristics, and the radiometric calibration of the Landsat-4 MSS bands relative to the characteristics of the preceding Landsat sensors.

If detectors within a band are not perfectly calibrated with respect to each other (i.e., equalized), image banding results and extra variability or noise is introduced into the statistical descriptions (e.g., signatures) of signals from specific scene classes. Similarly, if the noise associated with each detector channel were to significantly exceed design specifications, the utility of the data collected by the system would be diminished. Also, reduced dynamic range could degrade data utility.

Furthermore, if the radiometric calibration of the Landsat-4 MSS bands were not to match well that of its predecessors or were to drift, algorithms, techniques and procedures with fixed coefficients or thresholds developed for use with Landsat 1, 2 and 3 MSS scanners would have to be modified accordingly.

1.2 OBJECTIVES

The objectives of this investigation were to address the following two topics, relative to characterization of Landsat-4 image data quality:

(a) Detector calibration: The calibration of the six Landsat detectors in each band were to be studied in order to determine the magnitude of any calibration differences that remain after ground processing and, if needed, to provide information that would support corrective techniques.

(b) Satellite-to-satellite calibration: Calibration differences between Landsat-4 and previous Landsat satellites were to be studied and, as needed, a method developed to adjust Landsat-4 multispectral scanner (MSS) signals, in all four spectral bands, to match the calibration of previous MSS sensors.

In addition, we were to examine the overall quality and characteristics of Landsat-4 MSS data and make recommendations where possible that could improve the data quality.

2
APPROACH

An empirical approach involving several topics was pursued to assess the quality of Landsat-4 MSS image data. Data from the several frames described in Section 3 were obtained for analysis.

The first step was to compute and analyze signal statistics on a detector-by-detector basis for the six detectors in each of the four spectral bands on the "A" tapes.* Means, variances and histograms of signal amplitudes were computed for the entire frame, for four 600-line segments and 12 subsegments, and for several diverse scene classes. Within-band means and variances were compared to search for evidence of detector "banding" effects. Histograms were examined to compare the quantization patterns (a result of radiometric look-up tables) found in the signal amplitudes, both for the entire scene and for the image subsegments. Digital display maps were produced from these scenes and examined visually for banding effects. The detector-based statistics and Variable X vs. Variable Y scatter plots also were examined qualitatively for dynamic range and other characteristics, relative to our experience with previous Landsats.

Another approach used for detecting banding effects was the Fast Fourier Transform (FFT) technique. FFT's were computed of a down-track profile for each band for each frame; these profiles were obtained by averaging all pixels in each scan line. Spatial frequencies at integer wavelengths (e.g., six scan lines) that are

*An "A" tape is a computer-compatible tape which contains MSS scanner data that have only been radiometrically corrected, as opposed to "P" tapes whose data have also been geometrically corrected and radiometrically resampled. Both types of tapes are available from USDC/NOAA, EROS Data Center, Sioux Falls, SD 57198.

more pronounced than others at nearby frequencies are indicative of banding, and can give a quantitative measure of its magnitude.

FFT's also were computed for individual scan lines at selected locations in the frame. These results provided a mechanism for detecting and quantifying coherent noise effects in the image data, both amplitude and phase as well as between-band comparisons. This type of noise produces a pattern on images that appears as diagonal stripes.

The final topic addressed was satellite-to-satellite calibration. Landsat Path-Row locations and dates within the contiguous 48 states were identified where simultaneous coverage is possible by the Landsat 3 and Landsat 4 scanners. This possibility exists because of the 16-day and 18-day repeat coverage cycles of Landsat 4 and Landsat 3, respectively. Arrangements were made to have the Landsat-3 tape recorder turned on during those frames to acquire such data for subsequent analysis. The availability of simultaneous coverage eliminated several confounding effects from the analysis of relative radiometric calibration between these systems. One matching pair of frames from Landsats 2 and 4 was also identified and obtained.

The method used to analyze differences between Landsats 3 and 4, and 2 and 4, was to carefully extract polygons in each dataset that outlined the same areas in both satellite images. Signal means were computed for each area, and then regression analysis of these area mean statistics was used to determine the radiometric relationship and measure its accuracy. As a byproduct of this effort, the polygon positions themselves were used to measure the geometric consistency of data from the Landsat 3 and 4 satellites.

3
DESCRIPTION OF DATA SET

Table 1 identifies the Landsat data used for the analyses reported herein. The two Landsat 3/Landsat 4 frame pairs include one winter scene containing parts of Massachusetts, Vermont and New Hampshire, and one autumn scene containing the east coast of North Carolina. The Landsat 2/Landsat 4 pair covers the south eastern corner of New Mexico.

In addition, two unpaired Landsat 4 frames (September 1982) were used for radiometric quality analysis. One of these is on the border of North and South Carolina, and is composed primarily of forests and pasture, with some agricultural fields. Dynamic range in this scene is limited, possibly due to the limited scene classes or to the presence of haze. The other frame covers the Imperial Valley of California at the border with Mexico, and contains the diverse scene classes of a highly productive agricultural area, a large inland lake (Salton Sea), desert or semi-desert areas, and mountains. This diversity is reflected in a substantial dynamic range of the data.

TABLE 1. DESCRIPTION OF DATA SET

Geographic Location	Landsat	Path/Row	Date	Frame
Carolina (inland)	4	17/36	29 Sep 82	40075-15271
California (Imperial Valley)	4	39/37	23 Sep 82	40069-17433
N.Carolina (coast)	3	15/35	24 Sep 82	31664-15070
"	4	14/35	24 Sep 82	40C70-15081
New England	3	14/30	22 Dec 82	31753-14591
"	4	13/30	22 Dec 82	40159-15010
New Mexico	2	34/37	9 Nov 82	22848-16571
"	4	32/37	9 Nov 82	40116-17005

4
RESULTS FROM DATA QUALITY ANALYSIS

In this section we discuss several topics, including banding, quantization effects, coherent noise and geometric considerations. First, some general observations on Landsat 4 MSS quality are presented. Results from our between-satellite calibration analysis are presented in Section 5.

4.1 QUALITATIVE COMPARISON OF LANDSAT 4 MSS WITH PREVIOUS MSS DATA

Data from the Landsat 3 and 4 MSS's were examined visually to see how well the two sensors correspond radiometrically. Figure 1 is an example of one such comparison for an agricultural area in North Carolina. The radiometric similarity is striking, a first suggestion that the two sensors provide comparable data.

Further evidence of this similarity was found in the examination of Landsat 4 data from Imperial Valley, California. In this scene, four distinct general scene classes were identified and scatterplots of Bands 2 and 3 were prepared for each class as well as for a comprehensive sample of the whole dataset. The distributions for the individual scene classes were marked on the comprehensive scatterplot, and this result is presented in Figure 2. From this figure, four observations can be made:

1) Water is represented by low signals in all bands
2) Sand is bright in all bands
3) Clouds are so bright as to cause signal saturation (level 127), at the prevailing solar illumination angle of 47° (elevation)

Landsat 4

Landsat 3

FIGURE 1. QUALITATIVE COMPARISON OF LANDSAT 3 AND 4 MSS DATA (NORTH CAROLINA, SEPT. 1982)

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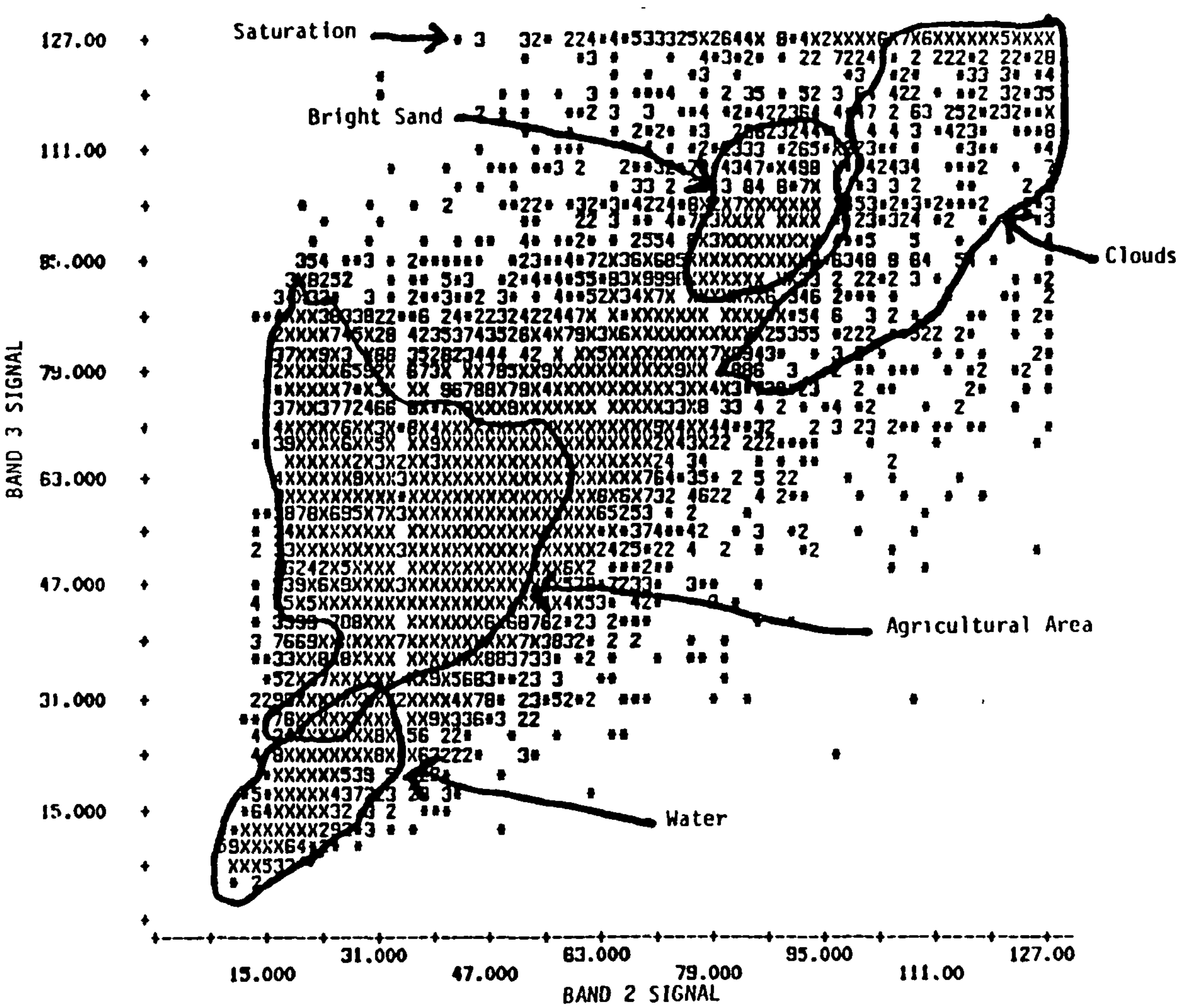


FIGURE 2. SPECTRAL DISTRIBUTION OF SCENE CLASSES FROM THE IMPERIAL VALLEY, CALIFORNIA SCENE

4) Agricultural data fill out a roughly triangular shape (a "tasseled cap")

All of these observations also are generally true for data we had examined previously from Landsats 1-3.

4.2 DETECTOR BANDING AND QUANTIZATION EFFECTS

In order to determine whether banding effects exist in Landsat 4 MSS data after radiometric correction, photographic images and other displays of the data were examined. Banding effects were visually noted only in areas of nearly uniform signal, such as water bodies and barren plains. One such area, shown in Figure 3, is a high-reflectance area near Imperial Valley, California.

To measure the magnitude of this banding effect, two techniques were used. The first of these techniques was to tabulate the signal mean for each detector within each of five areas in the Imperial Valley scene. Each area represented a different general scene class. Table 2 presents this information. The largest difference found between detector means was 0.88 of one count, and the RMS error was generally less than 0.3 counts, a very low error rate.

A more comprehensive estimate of residual banding error was made using Fourier analysis. Down-track FFT's were computed on scan line average signals on all bands of two Landsat frames*. An example of these FFT's is given in Figure 4. These FFT's were examined for response at a spatial wavelength of six pixels and the harmonics at three and two pixels. Disturbances were found at these wavelengths, that typically consisted of an upward spike with a modified pattern of response in the vicinity. By using the magnitude of the spikes, the average deviation from the mean of the six detectors was calculated. The largest average deviation, which occurred in the Carolina scene,

*40075-15271 29 Sep 82 Carolina; 40069-17433 23 Sep 82 California

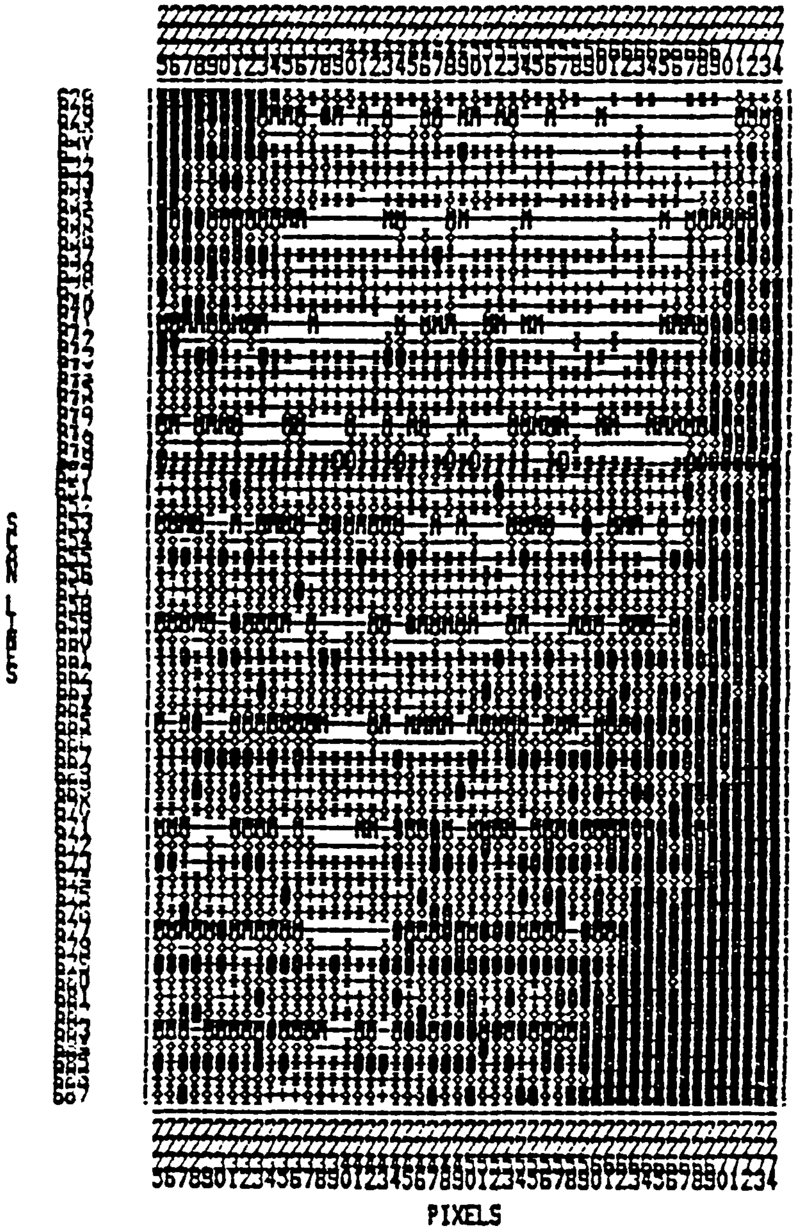


FIGURE 3. EXAMPLE OF THE DETECTOR BANDING EFFECT (BRIGHT SHALLOW VALLEY)

TABLE 2. DETECTOR AVERAGES FOR FIVE AREAS IN ONE LANDSAT 4 FRAME (IMPERIAL VALLEY, CALIFORNIA)

Detector	1	2	3	4	
1	23.01	21.08	36 80	14.44	
2	23.29	21.00	36.91	14.41	
3	22.94	21.10	36.94	14.53	
4	23.23	21.04	37.31	14.62	Highlands
5	23.25	20.97	37.18	14.43	
6	23.31	21.03	37.15	14.70	
=	.16	.05	.19	.12	
1	33.08	35.51	53.86	19.03	
2	33.38	35.78	54.18	19.09	
3	33.41	36.06	54.32	18.99	
4	33.32	36.10	54.22	18.80	Agricultural
5	33.31	35.86	53.60	18.81	
6	33.08	35.69	53.75	18.91	
=	.15	.22	.29	.12	
1	62.23	76.10	84.14	25.73	
2	62.11	76.76	84.25	25.62	
3	62.10	76.08	84.54	25.84	
4	61.42	76.01	84.04	25.89	Sand
5	61.78	75.88	83.81	25.84	
6	61.99	76.23	83.88	25.63	
=	.30	.31	.27	.12	
1	20.79	13.65	10 09	2.43	
2	21.02	13.69	9.88	2.35	
3	20.64	13.70	9.91	2.21	
4	20.73	13.52	9.59	2.27	Water
5	20.26	13.37	9.84	2.07	
6	20.81	13.90	10.22	2.30	
=	.25	.18	.22	.12	
1	51.62	61.55	69.43	22.10	
2	51.77	61.82	69.17	22.27	
3	51.58	61.58	69.30	22.44	
4	52.16	61.68	69.52	22.53	Bright Shallow
5	51.28	62.07	69.31	21.97	Valley
6	51.67	61.79	69.56	22.05	
=	.29	.19	.15	.22	

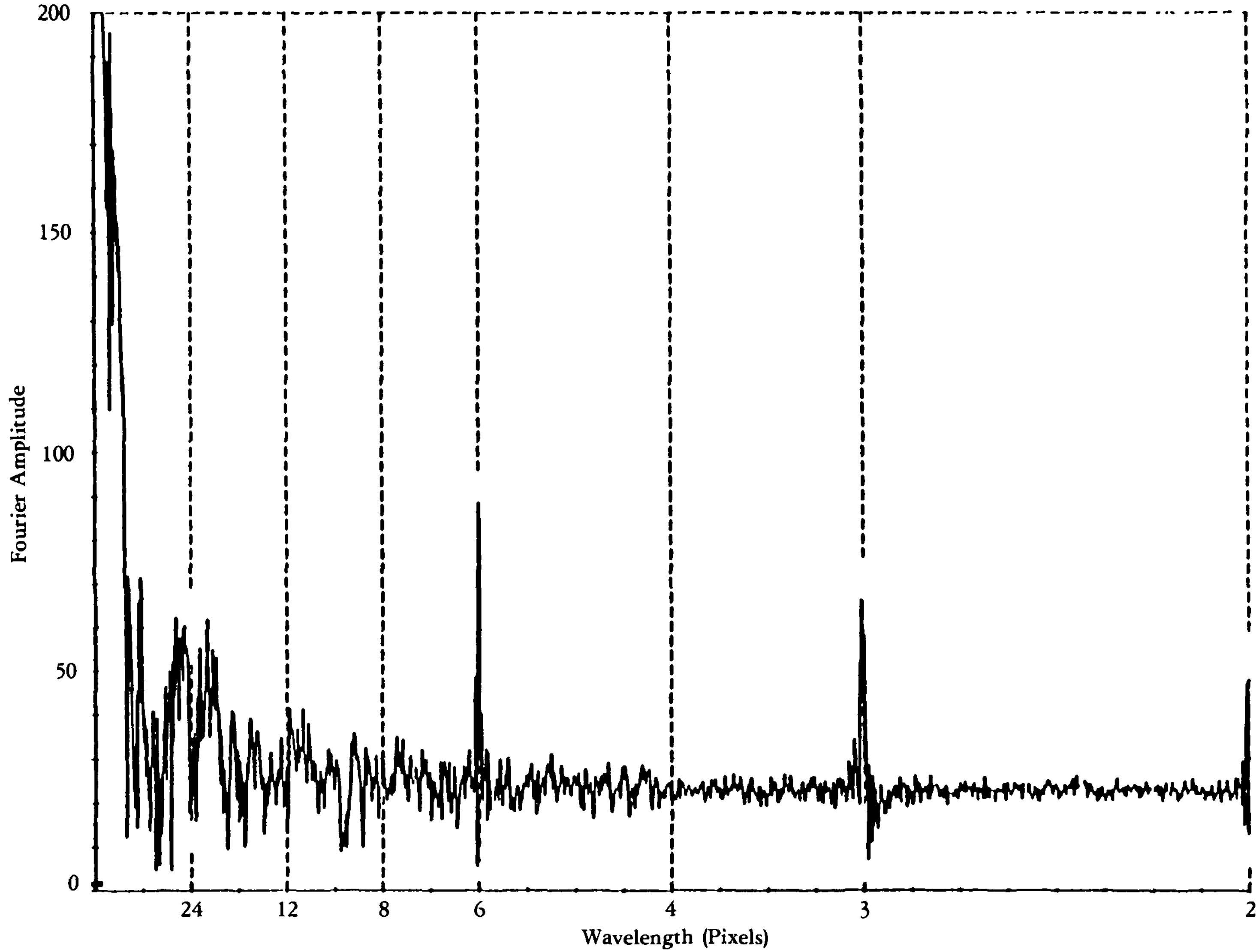
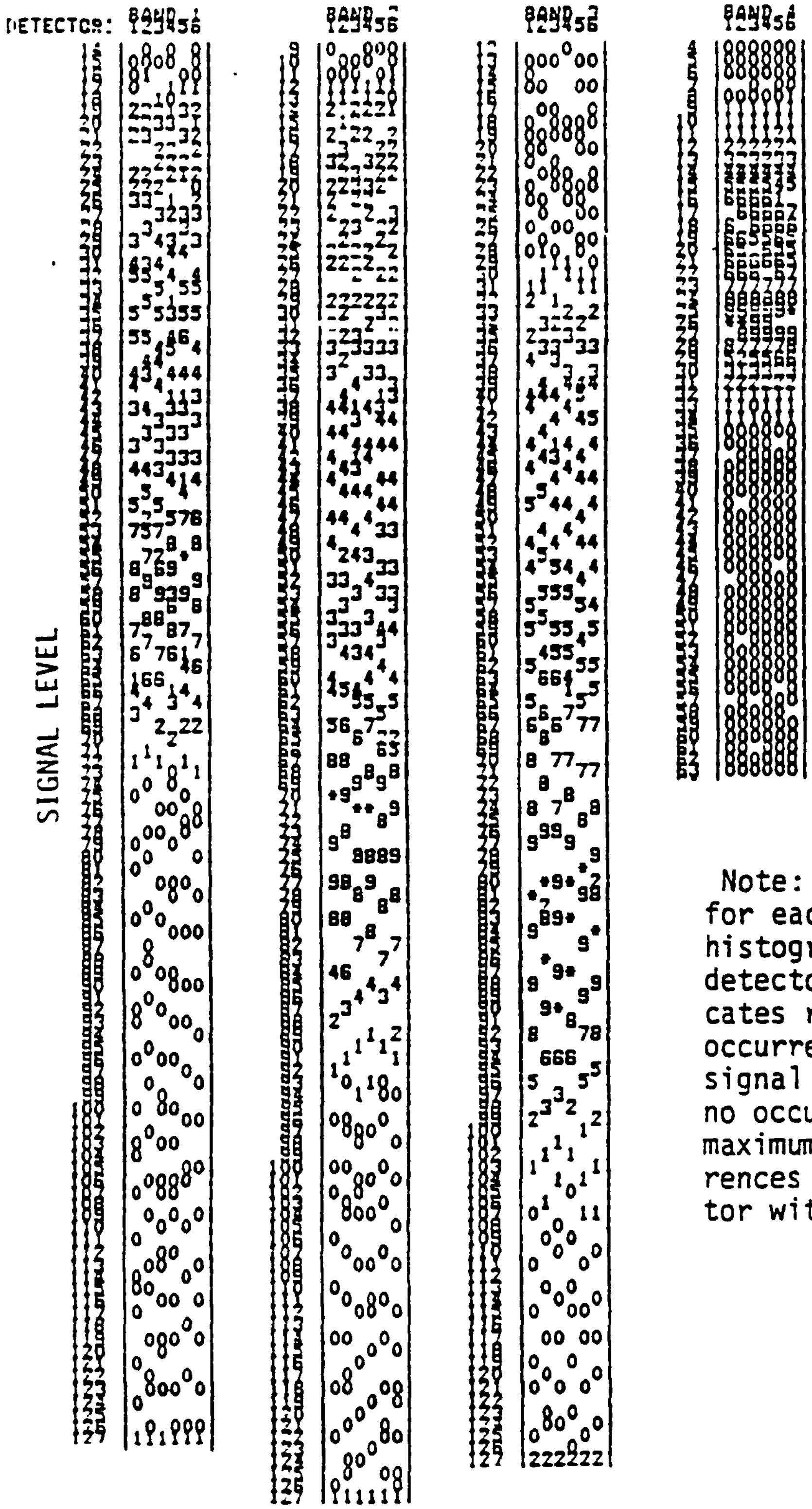


FIGURE 4. FOURIER TRANSFORM OF DOWN-TRACK AVERAGES, CHANNEL 1, CAROLINA SCENE

was 0.27 of one count and had a measurement error of about 0.05 due to scene information. This result based on FFT analysis is very similar to the result based on computing detector means.

The destriping or debanding algorithm used by the production system for full-frame MSS data sets [1] was examined to see if any further improvement seems possible. The algorithm carries out signal decompression (Bands 1-3 only), calibration wedge normalization, and detector histogram equalization using a single transformation of received satellite samples to determine final count levels. A separate transformation is computed for 600-scan-line blocks, then is interpolated to each 200-scan-line sub-block. Figure 5 shows an example of the resulting pattern of empty and full count level bins, a pattern which differs between detectors due to the correction. Examination of this pattern for a series of 200-scan-line blocks showed the expected gradual change from one block to the next, and indicated that the algorithm worked as intended.

A very important limit on accuracy of this destriping algorithm is not one of measuring differences or determining corrections, but rather one of translating corrected values to nonfractional count levels. The theoretical RMS error of this truncation process is 0.29 [2], which is similar to the error magnitudes reported above. That is, the current correction algorithm can't be improved much if any without dealing with the truncation error problem. This error could be reduced somewhat (per radiance unit) by using more numeric precision, for example by spreading the signal values over the range 0-255 instead of the current 0-127. However, the analog-to-digital conversion process in the satellite is another assignment to nonfractional values with the same 0.29 count RMS error, measured in the 6-bit numeric system used at the satellite. This on-satellite assignment can cause minor but uncorrectable banding which is most notable in relatively uniform areas.



Note: Each of six columns for each band represents one histogram for a specific detector. Each digit indicates relative number of occurrences at a specific signal level (blank means no occurrences, * means maximum number of occurrences found for any detector within each band).

FIGURE 5. EXAMPLE OF QUANTIZATION EFFECTS

4.3 THE COHERENT NOISE EFFECT

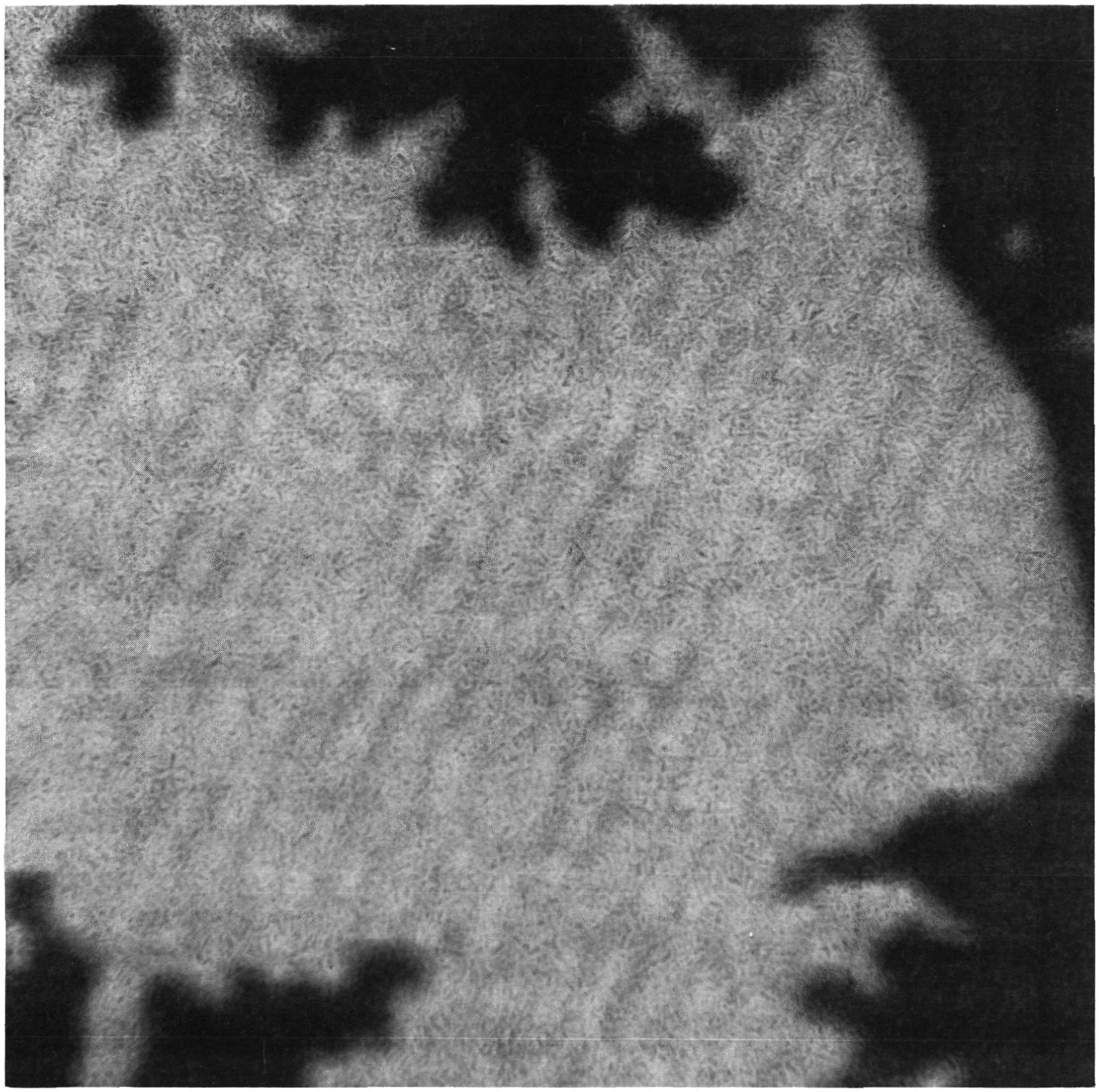
A careful examination of imagery from Landsat 4 MSS revealed a diagonal striping pattern, particularly in areas of nearly uniform radiance. An example of this pattern is presented in Figure 6.

A Fourier transform analysis of this noise pattern was carried out on selected scan lines distributed throughout two Landsat frames. As illustrated by Figure 7, it was found that the noise consisted of a dominant spatial wavelength of about 3.6 pixels along scan that was present in all bands. The frequency corresponding to the observed dominant wavelength is approximately 28 KHz. The wavelength was slightly different (3.57 compared to 3.59) for the two frames, but was consistent ($\pm$.001) within each frame. In one frame (South Carolina), two other wavelengths appeared somewhat consistently, namely the wavelengths of 2.02 and 4.63 pixels, but these and other smaller peaks in both frames were not analyzed in detail.

Figure 8 illustrates peaks at the principle wavelength, along with a number of additional peaks that are minor and inconsistent. The magnitude of the sine-wave component at the primary peak was computed and tabulated for the group of scan lines that was processed. This information, presented in Table 3, shows that the magnitude of the noise did not exceed one count in the worst band (Band 1), and is a relatively minor source of error in spite of its nuisance effect on images of uniform areas. (The error magnitude in Band 4 was scaled in order to match calibration in use after October 20. Questions of calibration are discussed in Section 5.)

4.4 GEOMETRIC DISTORTION

In carrying out the radiometric work described in this report, a significant geometric distortion was noted in the "A" tapes used in the analysis. This distortion is characterized by adjacent groups of six scan lines (each group comprising one mirror sweep) displaced relative to one another, as illustrated in Figure 8. The magnitude of



PIXELS

FIGURE 6. EXAMPLE OF DIAGONAL STRIPING (COHERENT NOISE) IN SOUTH CAROLINA SCENE, WATER AREA

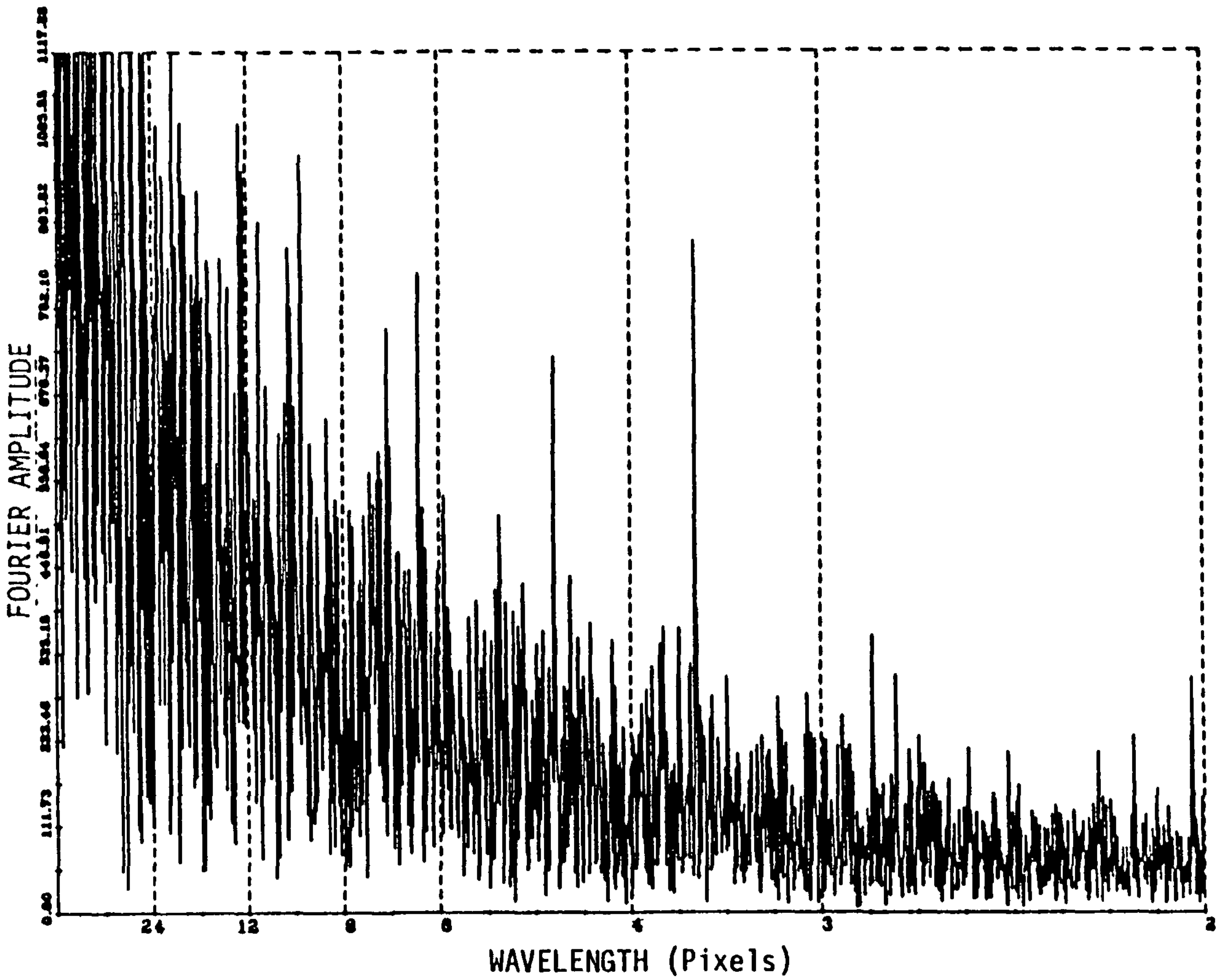
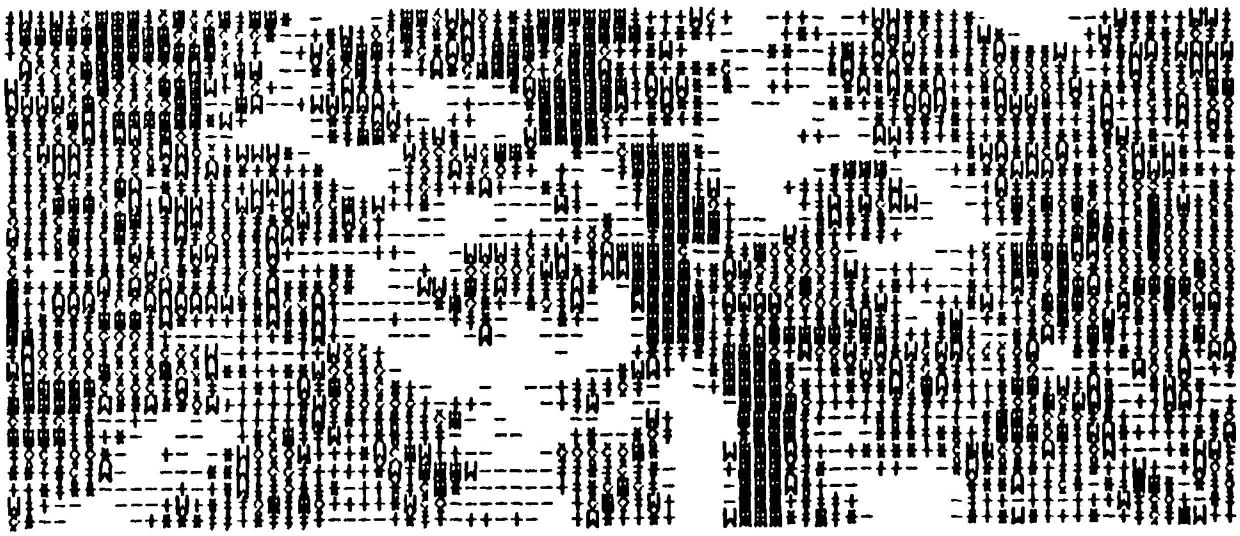
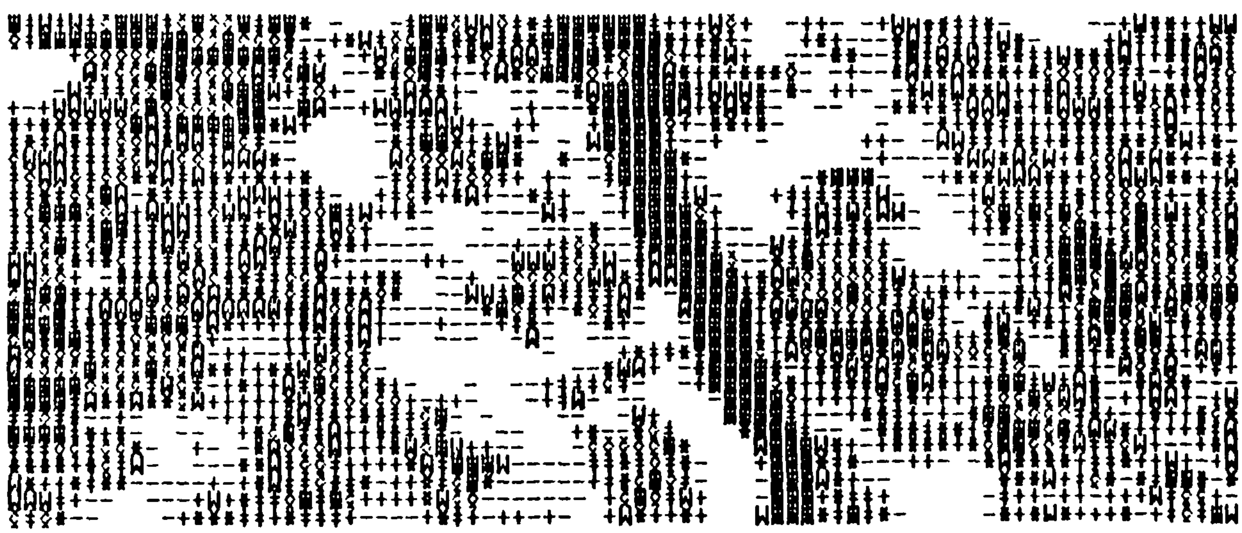


FIGURE 7. ALONG SCAN FOURIER TRANSFORM SHOWING COHERENT NOISE PEAK AT WAVELENGTH 3.6 (SOUTH CAROLINA, SCAN LINE 2117, BAND 3)



Before Correction



After Correction

FIGURE 8. LINE LENGTH VARIATION IN LANDSAT-4 MSS "A" TAPES

TABLE 3. AVERAGE MAGNITUDE OF COHERENT NOISE EFFECT

Band	Magnitude (counts)
1	0.75 ± .11
2	0.52 ± .09
3	0.56 ± .10
4	0.50 ± .10*

*This Band 4 value has been scaled to reflect the calibration of data produced on or after 20 October 1982.

the displacement varied up to six pixels, and decreased to zero at the left side of the image, indicating that the distortion is a line length variation. We found that this distortion was absent or much reduced in one scene taken when the Thematic Mapper (TM) sensor was not operating.

For further analysis of the scenes acquired with the TM operating, we implemented a linear line stretch correction, based on the position of end-of-scan codes in each scan line, that we understand is equivalent to the correction used to produce the geometrically corrected Landsat 4 "P" tapes. This correction substantially improved the geometric correspondence between paired Landsat 3 and 4 datasets. As Figure 8 shows, this correction restored the Connecticut River to its proper contiguous course.

By using accurately located, paired, Landsat 3 and 4 field definitions that were prepared for the between-satellite calibration work described in Section 5, we were able to perform one simple test of geometric accuracy of "A" tapes. Regression analysis was used to form a linear relation between the mean field location in Landsat 4 and that location in Landsat 3. The standard error of that relation is a measure of how geometrically consistent the two sensors are before geometric corrections are applied. It was found, based on the 60 well-dispersed fields in the New England site, that the variation of pixel location was 1.8 and of scan line location was 0.8. Since we judge that the polygons were located with a local accuracy of about 0.5 pixels, other error, such as nonlinear mirror sweep rates, could explain this result. (The polygons were located in Landsat 4 data after the linear stretch correction was applied.)

5
RESULTS FROM ANALYSIS OF BETWEEN-SATELLITE CALIBRATION

In order to ensure for the Landsat users community a means to achieve consistent interpretability of Landsat data, it is necessary to calibrate one Landsat to another. This means that a specific signal value from two separate Landsat MSS sensors would be made to correspond to the same radiance by the use of a calibration transformation. Algorithms developed using data from one Landsat MSS sensor could then be made applicable to another.

An example of this situation is a data screening algorithm [3] in which decision boundary boundaries are used to distinguish clouds, water and cloud shadows from other areas in the scene. If the algorithm is to be applied to data from a new satellite, then the new data must have the same calibration, or else the fixed decision rules will give incorrect results.

In this section we describe the development of between-satellite calibration relations involving Landsat 4 MSS data. Appendix A summarizes previously developed calibration relations among the first three Landsats and presents the various combinations of these relations for all satellites in a convenient form for practical application.

5.1 MATCHING DATA SETS

The development of the required calibration information ideally would use measurements made on a common set of targets by the two sensors being compared. The measurements should be taken under comparable conditions or be made comparable by appropriate manipulations.

By far the best way to achieve comparability is to have the two sensors cover the same area at the same time from the same viewpoint. The consistent 18-day repeat cycle of Landsats 1, 2 and 3, did not allow such simultaneous measurement, since the orbits of successive satellites were generally displaced in time by nine days. However, the orbit of Landsat 4, with its 16-day repeat cycle, provided the occasional opportunity for simultaneous measurement that we exploited successfully.

In order to identify where the needed coverages would occur, Landsat 3 and 4 nominal frame center locations were plotted. Only areas in the contiguous U.S. were considered, since expedient availability of collected data was expected only for the U.S. Three loci of frame centers were found along which Landsat 3 and 4 ground paths coincided so as to permit similar view directions to scene objects. One locus passed along the East Coast from Florida to Maine; another covered a path from Texas through Iowa and Upper Michigan; a third proceeded from Los Angeles to Montana. The three loci are plotted in Figure 9.

To determine times of coincidences, the 18- and 16-day repeat coverage intervals were then evaluated. The two outside loci allowed repeated coincident coverage every 144 days (144 is the least common multiple of 18 and 16), but the middle one had coverages no closer than one day apart and so was not useful for our purposes.

The date and location of all potential occurrences of coincident coverage between September 1982 and March 1983 (the scheduled period during which both satellites would be operationally collecting MSS data) are presented in Table 4. Since this period exceeds 144 days, the table can be extrapolated forward (or backward) in time by multiples of 144 days to identify all coincidences in the contiguous U.S. that could occur if the nominal orbits were maintained.

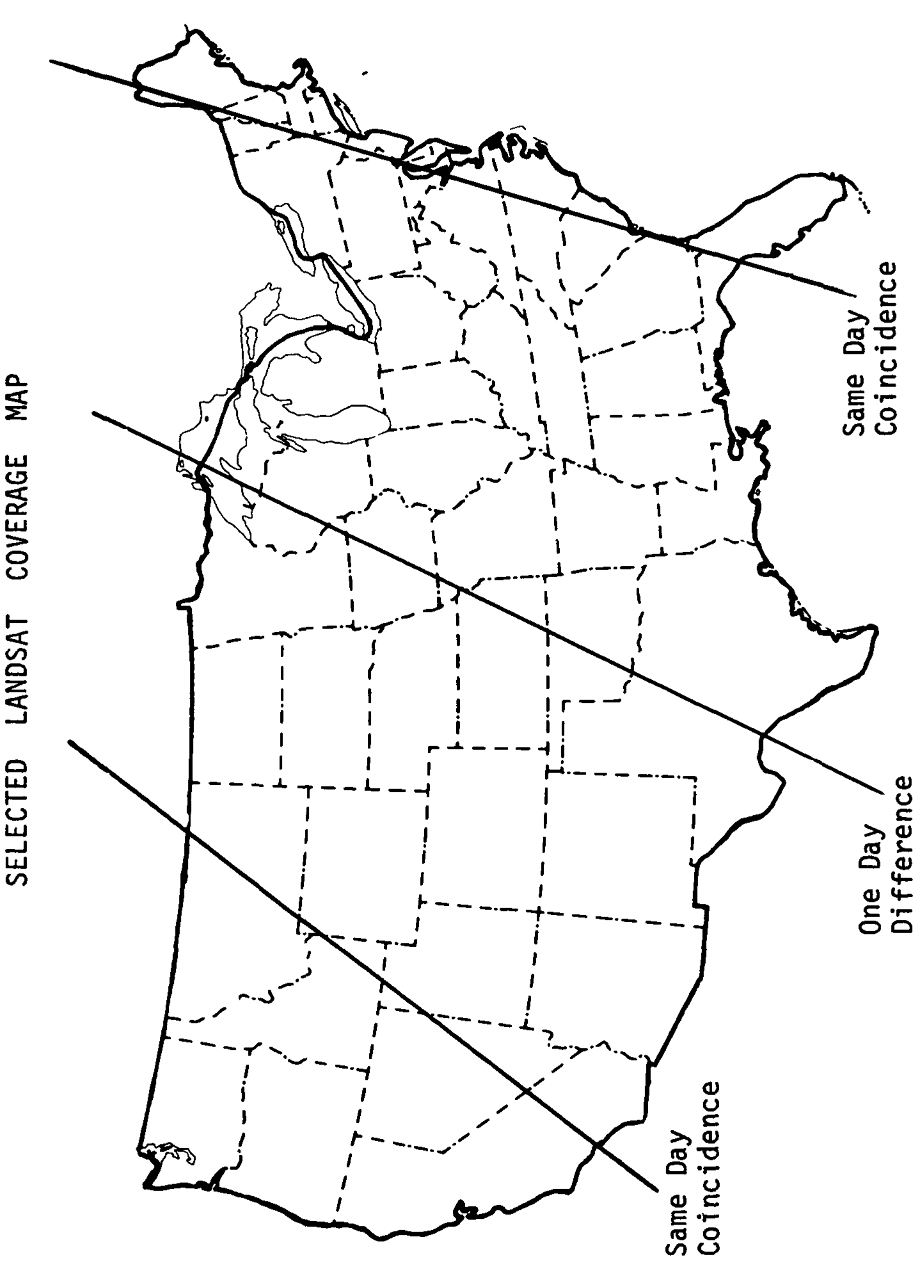


FIGURE 9. LOCI OF FRAME CENTERS WITH POTENTIAL COINCIDENT COVERAGE BY LANDSATS 3 AND 4

TABLE 4. TIMES AND PLACES OF POTENTIAL LANDSAT 3/LANDSAT 4 COINCIDENT COVERAGES IN THE CONTIGUOUS U.S.

Date	Landsat 3 Path*	Landsat 4 Path	Landsats 3 & 4 Row* Range	Place
Sep 24, '82	15	15	29-31	East NY... Chesapeake Bay
Oct 2, '82	41	38	27-31	Northern Utah... Mid-Montana
Oct 15, '82	18	17	37-40	S. Carolina... Tampa Bay
Oct 23, '82	44	41	35-36	Los Angeles...NE
Nov 18, '82	16	15	32-35	Harrisburg VA... Raleigh NC
Nov 26, '82	42	39	30-32	Eastern Idaho
Dec 17, '82	45	42	36 & South	Los Angeles & Southwest
Dec 22, '82	14	13	25-31	New England
Jan 12, '83	43	40	32-35	North & South Carolina,
Jan 20, '83	43	40	32-35	Eastern Nevada
Feb 15, '83	15	14	29-34	Eastern NY... Chesapeake Bay
Feb 23, '83	41	38	27-31	Northern Utah... Mid-Montana
Mar 8, '83	18	17	37-40	S. Carolina... Tampa Bay
Mar 16, '83	44	41	35-36	Los Angeles...NE

Several of these potential coincident-coverage datasets were requested and approved for collection. After losses due to cloud cover and acquisition problems were incurred, collection of coincident Landsat 3 and 4 data was successful on six dates, five of which are acquisitions in the U.S. Furthermore, although Landsat 2 has not been collecting MSS data operationally since February 1982, it was brought to our attention* that a coincident Landsat 2/Landsat 4 dataset was collected in November 1982. These known available coincident-coverage datasets are listed in Table 5.

5.2 FORMING CALIBRATION RELATIONSHIPS

In this investigation, three pairs of simultaneous coverage datasets were able to be used in forming between-satellite calibration relationships. These are listed in Table 6.

For each dataset pair, relatively large and uniform polygonal areas were carefully identified and located in the Landsat 4 data and also in the matching Landsat 3 or 2 data. The areas were selected to provide as wide a spectral range as possible. Field mean statistics were extracted and a linear regressions were run in each band to determine relations between the two satellites. The form of the relations used was:

$$\begin{matrix}\text{[Landsat 3 signal]} \\ \text{or} \\ \text{[Landsat 2 signal]}\end{matrix} = \text{gain} * \text{[Landsat 4 signal]} + \text{offset}$$

*We acknowledge William Likens, AMES Research Center, National Aeronautics and Space Administration, Moffet Field, California, for identifying these Landsat 2/Landsat 4 coincident coverage data.

TABLE 5. COINCIDENT LANDSAT MSS COVERAGES THAT WERE SUCCESSFULLY COLLECTED

Date	Landsats	Landsat 4 Path/Row	Comments
24 Sep '82	3 & 4	14/35-36	North Carolina Coast
9 Nov '82	2 & 4	32/37	New Mexico
22 Dec '82	3 & 4	13/29-32	New England
12 Jan '83	3 & 4	16/34-38	Carolina, Virginia
20 Jan '83	3 & 4	40/34-37	Southern California
23 Feb '83	3 & 4	38/25-30	Central Montana
25 Feb '83	3 & 4	189/20-24	(Landsat 3 path 204) Europe

TABLE 6. SUMMARY OF COINCIDENT DATASETS USED IN THIS INVESTIGATION

Location	Date	Landsats	Row	Number of Fields Used	Average Field Size (pixels)
Carolina Coast	24 Sep '82	3 4	35	12	574
New England	22 Dec '82	3 4	30	60	143
New Mexico	9 Nov '82	2 4	37	15	249

For Landsats 3 and 4, two separate sets of tranformations were determined, and these are presented in Table 7. Since the two results were not identical they were not combined. Instead, we recommend for use the results from the New England dataset, for three reasons. As shown in Table 6, the New England relationships were based on significantly more fields (60 rather than 12). Further, the Carolina scene seemed to have a significantly greater haze content, especially along the coast, that could have accentuated the effect of view angle differences between the satellites. Finally, the New England scene was acquired in December 1982 rather than September, so that if any calibration drift occurred during the early months of Landsat 4 operation, the New England relationships are more likely be representative of recent data.

To contrast the effects of using various forms of data correction, Table 8 was prepared. This table indicates that between 2 and 12 counts of error would occur, using an Euclidean count difference measure, if Landsat 4-calibrated data would be used instead of Landsat 3. However, if pre-launch measurements of calibration are used to correct the difference, the error is still between 3 and 9 counts, an insubstantial improvement. Table 8 also shows that if the New England relationships are right but Carolina ones are used anyway, there would be a difference only of between 1 and 3 counts. When this difference is considered to be a rough guide to accuracy of the relationships, a clearly important accuracy improvement is shown to occur when data are corrected by the relationships. More discusion on accuracy is presented in the next subsection.

Likewise, the set of transformations for Landsats 2 and 4 is presented in Table 9.

TABLE 7. EMPIRICAL LANDSAT 4-TO-3 CALIBRATION COEFFICIENTS

Scene	Band	Gain	Offset	SE*	R^2
New England	1	1.018	-1.614	0.52	0.996
	2	1.112	0.018	0.45	0.999
	3	0.9096	-0.463	0.53	0.999
	4	1.148	-0.421	0.53	0.998
N. Carolina	1	0.962	-0.164	0.41	0.992
	2	1.096	0.499	0.46	0.998
	3	0.861	0.558	0.67	0.999
	4	1.145**	-0.546	0.88	0.999
[Prelaunch	1	0.894	-1.00		
Calibration***]	2	1.000	0.722		
	3	0.863	0.870		
	4	1.026	2.34		

*SE = standard error in signal counts

**The N. Carolina scene was produced with the pre-October calibration, but this number has been converted to the post-October calibration form as described in text.

***This information represents carefully conducted ground measurements taken before launch of each satellite [1,4], along with a desired scaling of the data.

TABLE 8. COUNT DIFFERENCE COMPARISONS FOR LANDSAT 3-TO-4 CORRECTIONS, USING THE NEW ENGLAND CALIBRATION RELATIONS AS A STANDARD

Correction Used	Band	Landsat 4 minus "corrected" Landsat 3 signals*		
		Dark Field	Intermediate	Bright Field
No Correction	1	1.4	1.1	0.7
	2	-0.7	-4.0	-6.5
	3	0.9	4.9	7.2
	4	-0.2	-4.5	-6.2
	Composite**	1.8	7.8	11.5
Prelaunch Calibration	1	-0.8	-3.4	-6.0
	2	0.0	-3.3	-5.8
	3	1.3	-1.1	-2.4
	4	2.2	-1.3	-2.6
	Composite**	2.7	5.0	9.1
Carolina Calibration	1	0.9	-0.2	-1.3
	2	0.4	-0.1	-0.4
	3	0.9	-1.6	-3.0
	4	-0.1	-0.2	-0.2
	Composite**	1.3	1.6	3.3
Landsat 4 Base Value***	1	11	30	49
	2	6	36	58
	3	5	49	74
	4	4	33	45

*The count differences were produced by first transforming Landsat 4 base values to Landsat 3 form using the New England relation, then transforming from Landsat 3 form to Landsat 4 form by applying the stated corrections in the inverse direction, and finally subtracting.
this result from the original Landsat 4 base values.

**The band composite is computed as the square root of the sum of squared count differences over the four bands (Euclidean distance), as an aid in making comparisons.

***Absolute counts.

TABLE 9. EMPIRICAL LANDSAT 4-TO-2 CALIBRATION COEFFICIENT

Scene	Band	Gain	Offset	SE	R^2
New Mexico	1	0.8766	-0.592	0.96	0.973
	2	1.0124	2.187	1.12	0.989
	3	0.8796	1.699	0.97	0.995
	4	1.1002	-2.629	0.59	0.997
(Prelaunch Calibration	1	0.894	-2.988		
	2	1.035	-1.494		
	3	0.863	-1.740		
	4	1.026	-0.334		

When the Euclidean count difference measures were computed for this Landsat 2/4 transformation set, as they were for the Landsat 3 set, a similar picture emerged. Based on accepting this transformation set as correct, from 4 to 10 counts of error occurred when no correction was applied, and about 6 counts of error occurred when the transformation set based on prelaunch calibration was applied.

5.3 ANALYZING POTENTIAL SOURCES OF ERROR

The regression analyses used as described above to form calibration relations, also capably identify the precision of those relations. As noted in Tables 7 and 9, this precision (standard error) was about 0.5 of a count in all bands for the New England relations for Landsats 3 and 4, and up to one count for the New Mexico relations for Landsats 2 and 4.

While this indicated level of imprecision is commendably small*, other potential sources of error (bias) could be present. Table 10 presents information relating to the chief of these potential error sources, which are view angle differences, sun angle differences, and possible scenic changes in the brief interval between overpasses.

The degree of scenic change, such as possible variation in atmospheric haze or in vegetative response to heat or sun angle, are not known. However, since the elapsed time between overpasses is between 1 and 4 minutes, such changes are believed to be negligible, except possibly in the cases of the New Mexico relations, as discussed below.

*Relations previously determined among Landsats 1, 2 and 3 (see Appendix A) were based on much more tenuous associations of data acquired 9 days apart. These previous relations exhibit a larger standard error, due to unknown atmospheric and scenic differences.

The sun zenith angle differences were calculated (Table 10), and the effect on the calibration was estimated on the basis of a cosine model* [5]. The slight sun angle differences affected the signals by less than half a digital count (usually much less), an amount less than the standard error of regression. We did not adjust the calibration relations by this amount, primarily because the amount was so small. In practical situations that require calibration adjustments such as presented in this section, it is likely that normalization of much larger sun angle differences between scenes would also need to be applied before the scenes would be comparable.

In order to investigate the question of how serious an effect view angle differences may have, the New England frame pair was assigned a large number (60) of polygonal areas, and these areas were dispersed widely throughout the scene. The method of dispersal used was to define 20 subregions, positioned uniformly across scan, but randomly down track, then to subjectively select three uniform polygonal areas within each subregion to achieve a wide mix of signal levels. This method of dispersal ensured that any important dependence on view angle would be detected. Since Landsat 4 has a lower orbit than Landsat 3 (705 km rather than 920 km), the view angle difference at the end of a scan line would be about two degrees if the view angle at scene center is the same. No statistically significant relationship with differential view angle was found, indicating that two to three degrees of view angle difference did not introduce an error in the results greater than the standard error already presented.

*The cosine model states that the overall brightness of a scene is proportional to the cosine of the solar zenith angle, so that the scene can be normalized by dividing all signals by that cosine.

TABLE 10. DIFFERENCES IN MEASUREMENT CONDITIONS FOR THREE COINCIDENCE PAIRS

Coincident Scene	Landsats	Difference in: Estimated View Angle (Degrees)	Difference in: Sun Zenith Angle (Degrees)	Difference in: Time of Overpass (Minutes)
Carolina Coast	3 4	1.2	0.15	1.3
New England	3 4	0.9	0.15	1.8
New Mexico	2 4	2.9	0.24	3.7

A further possible source of error may be introduced by calibration drift of the sensor that can occur over time. Although the effect is minimized by the post-launch calibration procedure [1], which fixes the relationship between detector response and calibration lamp output, the amount of drift that remains after this calibration processing is an unknown.

The presented Landsat 4-to-2 calibration appears to contain more error than does the Landat 4-to-3 calibration, as is indicated by the larger standard errors (especially in Bands 1-3) and smaller R^2 values. Part of this greater error could be due to differences in area location accuracies (the areas were harder to locate in the Landsat 2/4 images), although scenic differences in the four-minute interval also are possible. The scene involved numerous clouds with some obvious changes in cloud patterns between overpasses. The weather at the site was in the process of clearing after the low clouds, drizzle and fog that prevailed at 8 AM (by 11 AM the clouds were mostly gone, humidity had decreased sharply and the wind had begun to veer westerly). Although fields were located away from clouds and cloud shadows, patterns of haze variation could have been moving in the scene.

A final pitfall to avoid in interpreting the calibration results is the possibility of overlooking calibration changes that may be made from time to time due to changes in ground processing coefficients. For Landsat 4, one such change occurred on 20 October 1982, at which time the gain of Band 4 was increased by a factor of 127/63. Another Landsat 4 change occurred on 1 April 1983 as described in Reference [6]. The transformations presented above were made to relate to the post-October but pre-April calibration, and they must be converted in order to apply to the post-April calibration, using relations that are presented in Appendix A.

6
CONCLUSIONS

The results of the analyses performed provide good evidence that Landsat 4 data are of the same high quality as previous Landsats, with a comparable dynamic range and target response, a good detector equalization procedure, and an accurate linear response to received radiance. Only two artifacts not noted in previous Landsats were found, and they were quantified. One is a geometric scan line length variation in Landsat "A" tapes, and was shown to be fairly well correctable with an algorithm like that reportedly employed in routine processing by the EROS Data Center. The other artifact is a coherent noise effect in all bands, having an amplitude of less than one count. This noise causes a minor diagonal striping pattern on images of relatively uniform areas and would require substantial processing to be routinely removed or reduced.

A well-defined linear relationship was determined to adjust Landsat 4 signals so they follow a radiance response characteristic equivalent to that of Landsat 3. Based on less data from a single matched pair of frames, a similar relationship was determined for Landsats 2 and 4.

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Appendix A

PRESENTATION OF KNOWN BETWEEN-SATELLITE CALIBRATION TRANSFORMS AMCNG LANDSATS 1 THROUGH 4

Prepared by: Thomas Parris and Daniel Rice

The purpose of this Appendix is to present the currently known satellite calibration coefficients that are based on empirical post-launch comparisons. The coefficients take the form

$$y_i = x_i a_i + b_i \qquad 1 \leq i \leq 4$$

where

x_i is the raw signal value for the i^{th} channel*
y_i is the corrected signal value for the i^{th} channel
a_i is the gain coefficient for the i^{th} channel
b_i is the offset coefficient for the i^{th} channel

Notation used in this Appendix includes the following:

MDP	Master Data Processor (used to produce Landsat full-frame products after approximately 1979.
preMDP	System(s) in use before the MDP for Landsat full-frame processing.
LACIE	A system used to produce 5x6 mile exerpts of Landsat data for the Large Area Crop Inventory Experiment.
MIPS	MSS Image Processing system, currently in use for all Landsat 4 data.
L1	Landsat 1, any date.
L2a	Landsat 2, before 16 July 1975.
L2b	Landsat 2, after 16 July 1975.
L3	Landsat 3, any date.
L4a	Landsat 4, before 20 October 1982.
L4b	Landsat 4, between 20 October 1982 and 31 March 1983.
L4c	Landsat 4, on or after 1 April 1983.

*For Landsats 1, 2 and 3 channel = band - 3
For Landsat 4 channel = band

This Appendix is divided into two parts. The first part presents the calibration coefficients in the form in which they were developed, along with a brief description of how the relations were produced. The second part involves compositions of one or more of the calibration relations presented in Part 1, to form a recommended set of transformations to a suggested standard calibration.

A.1 Original Calibration Transforms

A.1.1 L1-LACIE to L2-LACIE
L1-preMDP to L2-LACIE

This transformation should be used for Landsat 1 data processed either by LACIE or the predecessors of the Master Data Processor (MDP) [5,7]. The transformation is based on eight matched segment pairs, each pair representing Landsat 1 and 2 data acquired 9 days apart.

$$a = \begin{matrix} 1.04 \\ 1.00 \\ 1.09 \\ 0.82 \end{matrix} \qquad b = \begin{matrix} -5.79 \\ 1.19 \\ -2.91 \\ 3.01 \end{matrix}$$

A.1.2 L2b-preMDP to L2-LACIE

This transformation is based [7] on a small number of points from one segment in which the data were processed separately by LACIE and by a post-July 1975 full frame processor. Gains were established from published prelaunch data [8], and offsets were then established empirically. These gains and offsets were later substantiated by a 3-segment regression analysis carried out by Wacker [11].

$$a = \begin{matrix} 1.275 \\ 1.141 \\ 1.098 \\ 0.948 \end{matrix} \qquad b = \begin{matrix} -1.445 \\ -2.712 \\ -2.950 \\ 0.446 \end{matrix}$$

A.1.3 L3-LACIE to L2-LACIE

For Landsat 2 and 3 data processed by LACIE there are two sets of calibrations:

(a) These coefficients were developed by Lambeck at ERIM [4], based on matched cluster means from 21 pairs of segments separated by 9 days.

$$a = \begin{matrix} 1.1371 \\ 1.1725 \\ 1.2470 \\ 1.1260 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

(b) These coefficients were derived by Wehmanen [9] using similar methods.

$$a = \begin{matrix} 1.161 \\ 1.230 \\ 1.246 \\ 1.062 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.1.4 L3-MDP to L3-LACIE

There is uncertainty as to the correct transformation to match Landsat 3 MDP data with Landsat 3 LACIE data, or even whether the transformation is the same for all scenes. This situation is unfortunate since it is the key to connecting the calibration of early Landsats (1 and 2) with that of the later ones. Two conflicting theories exist.

(a) These coefficients are based on information stating that LACIE and preMDP processors used the same calibration, so are the same as A.1.8 for MDP.

$$a = \begin{matrix} 1.0 \\ 1.0 \\ 1.0 \\ 0.4961 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

(b) These coefficients are based on MDP data that have been further processed by LIVES (Landsat Image Verification and Extraction System) at NASA/Johnson Space Center, Houston, Texas. The data processed by LIVES were to have maintained the MDP calibration unchanged. The coefficients were determined by Wacker [11], who used a number of fields in 3 segments processed both by LACIE and by MDP/LIVES.

$$a = \begin{matrix} 1.007 \\ 0.898 \\ 0.896 \\ 0.437 \end{matrix} \qquad b = \begin{matrix} 2.038 \\ 0.734 \\ 1.378 \\ -0.461 \end{matrix}$$

A.1.5 L4c-MIPS to L4b-MIPS

Landsat 4 data processed after April 1, 1983 can be calibrated to Landsat 4 data processed after October 20, 1982 and before April 1, 1983 with the following coefficients, based on published information [6]. This represents a specific mathematical change in ground processing and, hence, is exact.

$$a = \begin{matrix} 1.026 \\ 0.909 \\ 1.087 \\ 0.864 \end{matrix} \qquad b = \begin{matrix} 0.009 \\ 0.000 \\ 0.008 \\ 0.005 \end{matrix}$$

A.1.6 L4b-MIPS to L3-MDP

Two other calibrations have been proposed for Landsat 4 MSS data processed October 20, 1982 and before April 1, 1983. These calibrations map the data to Landsat 3 (MDP).

(a) These coefficients were developed by ERIM (see Section 5 of this report), based on 60 fields in one full frame pair taken on the same day by Landsats 3 and 4 Regression accuracies were much higher than for previous between-satellite relationships since the acquisitions were nearly simultaneous.

$$a = \begin{matrix} 1.018 \\ 1.112 \\ 0.9096 \\ 1.148 \end{matrix} \qquad b = \begin{matrix} -1.614 \\ 0.018 \\ -0.463 \\ -0.421 \end{matrix}$$

(b) These coefficients were developed by Alford and Imhoff [12], using 9 fields in the identical full frame pair as in (a). This transformation provides essentially the same results as (a) above, within 1.5 counts (worst case Band 1) and 0.6 counts (worst case all other bands).

$$a = \begin{matrix} 0.97 \\ 1.10 \\ 0.92 \\ 1.15 \end{matrix} \qquad b = \begin{matrix} -0.82 \\ 0.30 \\ -0.53 \\ -0.48 \end{matrix}$$

A.1.7 L4b-MIPS to L2-MDP

The following coefficients map Landsat 4 data (processed after 20 October 1982 and before 1 April 1983) to Landsat 2 data, based on one full-frame pair acquired on November 9, 1982 (see Section 5 of this report). There could be some question about calibration drift of the aging Landsat 2 after the Landsat 3-Landsat 2 calibration data were acquired (in 1979 or before).

$$a = \begin{matrix} 0.8766 \\ 1.0124 \\ 0.8796 \\ 1.1002 \end{matrix} \qquad b = \begin{matrix} -0.592 \\ 2.187 \\ 1.699 \\ -2.629 \end{matrix}$$

A.1.8 L2b-MDP to L2b-preMDP
L3-MDP to L3-preMDP
L4b-MIPS to L4a-MIPS

Each of these transforms involves the change in scaling of Band 4, in which data values that vary from 0 to 127 must be changed to vary from 1 to 63, using the factor 63/127.

$$a = \begin{matrix} 1.0 \\ 1.0 \\ 1.0 \\ 0.4961 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.2 COMBINATIONS OF CALIBRATION TRANSFORMS THAT ACHIEVE A STANDARD

In this section we present a recommended set of transforms from each satellite and calibration type to a specific standard satellite and calibration type. For historical reasons, the standard used in this Appendix is Landsat 2 LACIE-calibrated data.

Data calibrated to the Landsat 2 LACIE standard are suitable for the following statement of the Tasseled Cap Transformation [7,13]:

$$t = Rx$$

where

x is the Landsat 2 (LACIE) equivalent signal value in column vector notation
t is the Tasseled Cap Feature Vector, and
R is the rotation matrix:

0.33231	0.60316	0.67581	0.26278
-0.28317	-0.66006	0.57735	0.38833
-0.89952	0.42830	0.07592	-0.04080
-0.01594	0.13068	-0.45187	0.88232

A.2.1 L1-LACIE to standard
L1-preMDP to standard

All Landsat 1 data can be transformed to the standard by using A.1.1:

$$a = \begin{matrix} 1.04 \\ 1.00 \\ 1.09 \\ 0.82 \end{matrix} \qquad b = \begin{matrix} -5.79 \\ 1.19 \\ -2.91 \\ 3.01 \end{matrix}$$

A.2.2 L2-LACIE to standard
L2a-preMDP to standard

$$a = \begin{matrix} 1.0 \\ 1.0 \\ 1.0 \\ 1.0 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.2.3 L2b-preMDP to standard

Using A.1.2:

$$a = \begin{matrix} 1.275 \\ 1.141 \\ 1.098 \\ 0.948 \end{matrix} \qquad b = \begin{matrix} -1.445 \\ -2.712 \\ -2.950 \\ 0.446 \end{matrix}$$

A.2.4 L2b-MDP to standard

Composing A.1.2 with A.1.8:

$$a = \begin{matrix} 1.275 \\ 1.141 \\ 1.098 \\ 0.470 \end{matrix} \qquad b = \begin{matrix} -1.445 \\ -2.712 \\ -2.950 \\ 0.446 \end{matrix}$$

A.2.5 L3-LACIE to standard

Using A.1.3.a:

$$a = \begin{matrix} 1.1371 \\ 1.1725 \\ 1.2470 \\ 1.1260 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.2.6 L3-preMDP to standard

Composing A.1.3.a with A.1.4.a and A.1.8 (the latter two cancel):

$$a = \begin{matrix} 1.1371 \\ 1.1725 \\ 1.2470 \\ 1.1260 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.2.7 L3-MDP to standard*

Composing A.1.3.a with A.1.4.a:

$$a = \begin{matrix} 1.1371 \\ 1.1725 \\ 1.2470 \\ 0.5586 \end{matrix} \qquad b = \begin{matrix} 0.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{matrix}$$

A.2.8 L4a-MIPS to standard*

Composing A.1.6 with A.2.7 and A.1.8:

$$a = \begin{matrix} 1.158 \\ 1.304 \\ 1.134 \\ 1.292 \end{matrix} \qquad b = \begin{matrix} -1.835 \\ 0.021 \\ -0.577 \\ -0.235 \end{matrix}$$

A.2.9 L4b-MIPS to standard*

Composing A.1.6 with A.2.7:

$$a = \begin{matrix} 1.158 \\ 1.304 \\ 1.134 \\ 0.641 \end{matrix} \qquad b = \begin{matrix} -1.835 \\ 0.021 \\ -0.577 \\ -0.235 \end{matrix}$$

*The assumption that A.1.4.a properly represents L3-MDP data is implicit in these flagged relationships.

A.2.10 L4c-MIPS to standard*

Composing A.2.9 with A.1.5:

$$a = \begin{matrix} 1.188 \\ 1.185 \\ 1.233 \\ 0.554 \end{matrix} \qquad b = \begin{matrix} -1.825 \\ 0.021 \\ -0.568 \\ -0.232 \end{matrix}$$

*The assumption that A.1.4.a properly represents L3-MDP data is implicit in these flagged relationships.

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