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Spectral Characterization of the Landsat-4 MSS Sensors

Relative spectral response data for the Landsat-4 MSS's are presented and compared to previous MSS's.

Introduction

Two multispectral scanner subsystems (MSS) have been fabricated and tested by Hughes Aircraft Company for the NASA Landsat program. The intention was to provide continuity with the MSS sensors on Landsats 1, 2, and 3. One MSS, designated the protoflight (PF) model, was integrated into the Landsat-4 spacecraft, which was launched on 16 July, 1982. The second, designated the flight (F) model, has been integrated into the Landsat-4 backup satellite, which is scheduled for possible launch in 1985. Each MSS has four bands in the reflective portion of the electromagnetic spectrum: (1) a green band, nominally 500 to 600 nm; (2) a red band, 600 to 700 nm; (3) a near-IR band, 700 to 800 nm; and (4) a second near-IR band, 800 to 1100 nm. On previous Landsats, these bands were known as MSS-4, MSS-5, MSS-6, and MSS-7, respectively, because the three-band return-beam vidicon (RBV) camera system occupied bands 1, 2, and 3. With the absence of the RBV camera system on Landsat-4, this designation is obsolete, and the MSS bands are referred to as 1, 2, 3, and 4, respectively. Each band consists of an array of six channels (i.e., six detectors and six filters). Thus, there are a total of 24 channels (i.e., four bands with six channels per band) that are numbered sequentially from 1 to 24 as follows: band 1 (channels 1 through 6), band 2 (channels 7 through 12), band 3 (channels 13 through 18), and band 4 (channels 19 through 24).

Abstract: *Relative spectral response data for the Landsat-4 and Landsat-4 backup multispectral scanner subsystems (MSS), the protoflight and flight models, respectively, are presented and compared to similar data for the Landsat 1, 2, and 3 scanners. Channel-by-channel (six channels per band) outputs for soil and soybean targets were simulated and compared within each band and between scanners. The two Landsat-4 scanners proved to be nearly identical in mean spectral response, but they exhibited some differences from the previous MSS's. Principal differences between the spectral responses of the Landsat-4 scanners and previous scanners were (1) a mean upper-band edge in the green band of 606 nm compared to previous means of 593 to 598 nm, (2) an average upper-band edge of 697 nm in the red band compared to previous averages of 701 to 710 nm, and (3) an average bandpass for the first near-IR band of 702-814 nm compared to a range of 693-793 to 697-802 nm for previous scanners. These differences caused the simulated Landsat-4 scanner outputs to be 3 to 10 percent lower in the red band and 3 to 11 percent higher in the first near-IR band than previous scanners for the soybeans target. Otherwise, outputs from soil and soybean targets were only slightly affected. The Landsat-4 scanners were generally more uniform from channel to channel within bands than previous scanners. One notable case of poor uniformity was the upper-band edge of the red band of the protoflight scanner, where one channel was markedly different (12 nm) from the rest. For a soybeans target, this nonuniformity resulted in a within-band difference of 6.2 percent in simulated outputs between channels.*

The engineering test data that were collected included channel-by-channel spectral response curves, detailing the relative response of each

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channel as a function of wavelength. Because this response is measured through the system's optics, it includes the combined effects of optics, filters, and detectors on the spectral response. A description of the test procedure is included in Appendix A. For previous MSS's, these data were contained in generally unavailable contractor reports to NASA (Norwood *et al.*, 1972; Felkel *et al.*, 1977). The primary intent of this document is to make available to the Landsat user community data on the spectral characteristics of these two sensors, including a characterization of the variability within and differences between the two sensors. These data can be used by individual investigators to assess the sensors' utility for their applications.

A second objective is to provide, through simulation, an estimate of the potential contribution of spectral differences between channels to within-band striping. In the remainder of this report, this type of striping will be referred to as "spectral striping." This should not be confused with "radiometric striping," which results from gain or offset differences between channels. Because spectral striping cannot be removed by uniform radiometric calibration, it limits the ability to remove banding from images.

One objective in placing an MSS on Landsat-4 was to provide continuity with the previous three Landsats. Thus, the Landsat-4 MSS's were designed, to the extent possible given the lower 705-km altitude of Landsat-4, to replicate the imagery of the previous MSS's. Therefore, a third objective of this document is to assess the extent to which the new MSS's match the previous MSS's in terms of spectral response.

Methods

Relative spectral response (RSR) curves for each channel (six in each of four bands) of the Landsat-4 PF and F multispectral scanners (Hughes Aircraft Company, unpublished reports, 1980; 1981), as well as the MSS's on Landsat 1, Landsat 2 (Norwood *et al.*, 1972), and Landsat 3 (Felkel *et al.*, 1977), were digitized at 10-nm intervals for bands 1, 2, and 3 and at 20-nm intervals for band 4. Two sets of curves were available for the PF scanner, one generated from data collected in June 1980 and one from data collected June 1981. The more recent set of curves was used to characterize the PF scanner.

The following attributes were computed from the digitized curves:

- Lower-band edge (50 percent relative response point)
- Upper-band edge (50 percent relative response point)
- Lower-edge slope interval (width between lower 5 and 50 percent response points)
- Upper-edge slope interval (width between upper 5 and 50 percent response points)
- Positive spectral flatness (maximum positive percent deviation from mean response in central 70 percent of nominal bandpass)
- Negative spectral flatness (maximum negative percent deviation from mean response in central 70 percent of nominal bandpass)

Although listed only under specifications for the filters (Table 1), these six characteristics were deemed appropriate for characterizing the overall relative spectral responses. In addition, the bandwidth (band edge to band edge) was calculated. For completeness, a characterization of the filter components for the PF and F models is included (Appendix B).

Each band was checked for anomalous channels (i.e., channels within the band that were significantly different from the rest). A modified F test (outlier test) was used for the screening (Grubbs, 1950) with an α-level of 0.01. Two parameters were calculated for each of the seven spectral characteristics for each band of each MSS: (1) the band mean (the average value of the characteristic for the six channels in the band), and (2) the band standard deviation (equal to the sample standard deviation using each channel as an observation). A statistical comparison between scanners of the band means and band standard deviations for each spectral characteristic was not possible because independent multiple measurements of each channel's spectral characteristics were not generally available. Two independent sets of measurements were available for the Landsat-4 PF scanner only. The approach used here was to consider an indicated difference between scanners in band mean or band standard deviation for a particular characteristic to be of consequence if it exceeded a specified value (threshold) determined from the differences between the two sets of PF relative spectral response measurements (Appendix C). The values used were

- 3 nm for means and 1.8 nm for standard deviations for band edges, widths, and slope intervals except as indicated below
- 33 nm for means and 2.7 nm for standard deviations for band 4 upper-band edge, width, and upper-edge slope interval
- 4 percent means and 0.9 percent standard deviations for positive and 6 percent means and 1.5 percent standard deviations for negative spectral flatness in bands 1 through 3
- 19 percent means and 2.4 percent standard deviations for positive and 12 percent means and 2.5 percent standard deviations for negative spectral flatness in band 4

A simulation procedure was established for assessing for each MSS the contribution of the channel-to-channel spectral differences to

TABLE 1. FILTER SPECIFICATIONS FOR LANDSAT MULTISPECTRAL SCANNERS

Band	Band Edge (nm) Half Power Points		Band Width (nm)	Slope Interval (nm) From 5% to 50%		Spectral Flatness (%) Over Central 70%	
	Lower	Upper		Lower	Upper	Positive	Negative
1	500 ± 10	600 ± 10	—	<20	<40	<5.0	<5.0
2	600 ± 10	700 ± 10	—	<20	<45	<7.5	<7.5
3	700 ± 10	800 ± 10	—	<20	<50	<5.0	<5.0
4	800 ± 10	1100[a] ± 10	—	<35	—	<5.0	<5.0

[a] Upper band edge not filter determined—filter specification necessary for flatness determination.

within-band target-dependent striping and for comparing the scanners' mean outputs to typical targets. Channel-by-channel digital MSS counts were simulated using field reflectance spectra.

Reflectance data of soil and soybeans collected with a Barnes Mark-II spectroreflectometer were used as input for the analysis. This instrument simultaneously samples incident sunlight and target-reflected light to provide target reflectance. Pertinent instrument characteristics over the spectral interval of 450 to 1150 nm are

- A sampling interval (filter position spacing) of 4 nm,
- An average spectral bandwidth of about 16 nm, and
- RMS noise of about 0.5 percent reflectance with a 50 percent reflective target (0.2 percent with a 3 percent reflective target) at a 35 degree solar zenith angle.

One spectrum of a moist soil plot and one of a soybean plot having a full canopy cover collected on day 226 in 1978 were used in this study. In addition to being common agricultural targets, soil and soybeans were selected because they were spectrally different. The spectrum of soybeans is characteristic of green vegetation (Figure 1).

The simulation procedure involved the following steps:

- Normalization of the relative spectral responses of the individual channels
- Conversion of narrowband target reflectance data to simulated radiances at satellite altitude, using an atmospheric and irradiance model
- Integration of narrowband radiances across each bandwidth, weighting by the normalized response coefficients (interpolated to match spectro-reflectometer sample points)
- Scaling the integrated radiances to match the output of the MSS

The procedure for normalizing the responses of the individual channels was designed to simulate the actual procedure that was used to calibrate the MSS channels during system testing. In the simulation program, the sensors "viewed" a spectrally flat target illuminated by a spectrally flat source, and correction factors were computed so that each channel gave the same output for this flat source. The calculation of a correction factor involved integrating the area under the RSR curve for the channel and dividing the result by the nominal bandwidth for the channel. A normalization factor was thus greater than one if the channel's bandwidth was effectively wider than nominal, and less than one if narrower than nominal.

In the actual MSS calibration a spectrally non-uniform target (integrating sphere) is observed. Postprocessing of the data, where each channel's spectral response and the integrating sphere's spectral output are known, allows the integrating sphere to appear spectrally flat (General Electric Co., "MSS Standard Interface Document," unpublished, 1978).

Conversion of the narrowband field measured reflectances to satellite level radiances was facilitated by wavelength specific additive and multiplicative factors obtained from the use of the Turner and Spencer (1972) atmospheric model. Inputs to the model included 40-degree solar zenith angle, 20-km horizontal visibility, 100 percent target reflectance, background reflectance

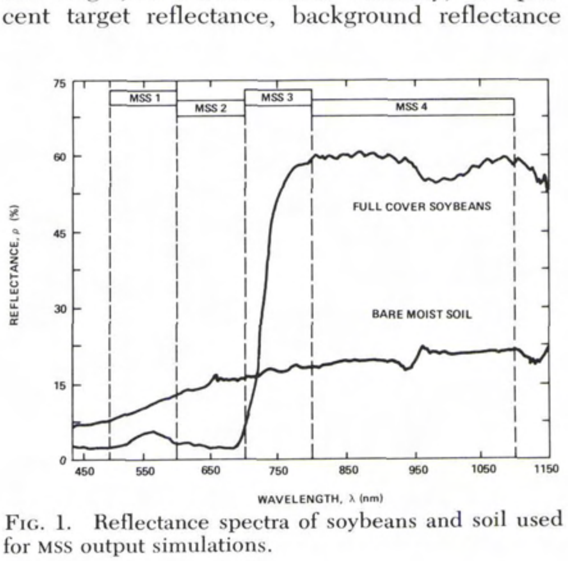

FIG. 1. Reflectance spectra of soybeans and soil used for MSS output simulations.

(average value for 50 percent soil/50 percent vegetated surface at a given wavelength), and 705-km satellite altitude. The use of the nominal Landsat 1, 2, and 3 altitude of 918 km would not have changed the atmospheric model's output. The two model output parameters used for each wavelength input were target-contributed (beam) radiance and path radiance. To determine the total satellite level radiance for a particular target, the beam radiance (for 100 percent reflective target) was multiplied by the target reflectance and the path radiance was added to the product. The Turner and Spencer model considers only atmospheric scattering (haze), which is the most important atmospheric factor in the MSS bandpasses. However, because water absorption does attenuate light in the region, particularly between 900 and 950 nm, the radiances obtained by this model are expected to be somewhat high in band 4.

The narrowband simulated radiances were then summed across the individual channels, weighted by the normalized relative response coefficients. The integrated radiances were then scaled to match the digital counts of decompressed MSS data. Bands 1 through 3 were linearly scaled from 0 to 127.99 counts and band 4 from 0 to 63.99 counts, using the given nominal saturation radiances of 2.48, 2.00, 1.76, and 4.60 mW cm^{-2} sr^{-1} for bands 1, 2, 3, and 4, respectively, to determine the scaling factors.

The simulation procedure can be described by the following equation, which is applied individually to each channel on each scanner:

$$\text{DN} = \text{SCFACT} \times \sum_{i=a}^{b} ([\text{REF}_i \times \text{BRAD}_i] + \text{PRAD}_i) \times \frac{\text{RESFAC}_i}{\text{NORFAC}} \times \text{WAVSPA}$$

where

- DN = simulated digital number output for MSS channel (nontruncated counts);
- SCFACT = scale factor for conversion of radiance to digital counts: Band 1, 51.61; band 2, 64.00; band 3, 72.73; band 4, 13.91 (counts/mW cm^{-2} sr^{-1});
- REF_i = target reflectance at i;
- BRAD_i = Turner model spectral beam radiance at i for 100 percent reflective target (mW cm^{-2} sr^{-1} μm^{-1});
- PRAD_i = Turner model spectral path radiance at i (mW cm^{-2} sr^{-1} μm^{-1});
- RESFAC_i = relative response factor of MSS channel at i;
- NORFAC = normalizing factor for MSS channel; and
- WAVSPA = wavelength spacing between spectrometer filter positions (nominally 0.004 μm).

Throughout the simulation, perfect relative radiometric calibration within bands and perfect absolute radiometric calibration for all scanners has been assumed. Also, equivalent radiometric calibrations for all scanners have been assumed, i.e., a given digital count in a band on one scanner corresponds to the same radiance value as on all other scanners. Thus, in this simulation, output differences between scanners are due solely to differences in their relative spectral responses. This contrasts to the real situation where calibrations of each scanner are different and performed with some error. In real data, radiometric factors could hide or overshadow spectral factors.

The band mean outputs to soil and soybeans (averages of six channels) were used to compare differences between PF and F and between PF, F, and the MSS's on Landsats 1 through 3. The maximum difference in output between channels within a band was used to compare the potentials for "spectral striping" among the scanners. Differences in means and maximum deviations were considered to be important if they exceeded

- 0.30 digital counts (approximate RMS quantization noise) and
- The differences in Table C-3 of Appendix C (differences between outputs simulated with two sets of PF measurements)

Results

Spectral characterization of Landsat-4 multispectral scanners: protoflight (PF) and flight (F) models

In most respects, the spectral responses of the PF and F (Figures 2 through 4) scanners are simi-

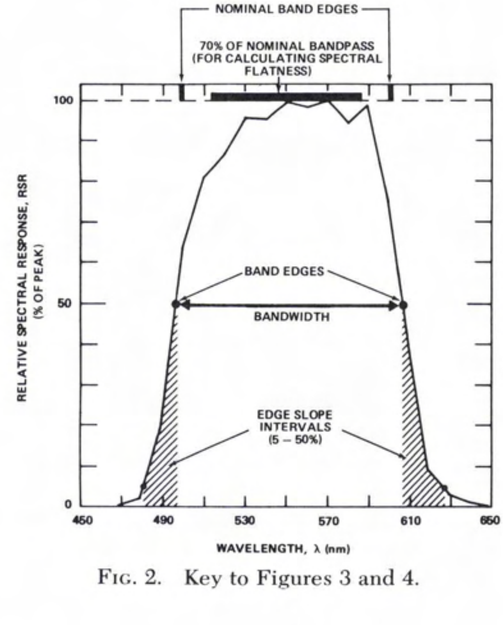

FIG. 2. Key to Figures 3 and 4.

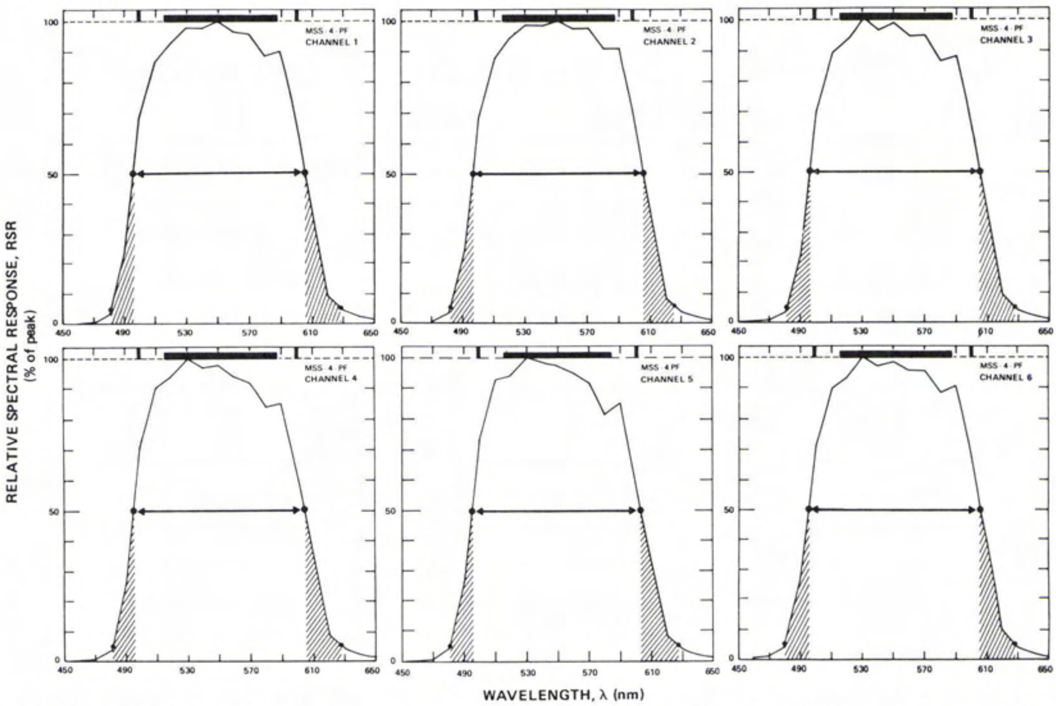

FIG. 3a. Protoflight model MSS (Landsat-4) relative spectral response curves from 1981 measurements (band 1).

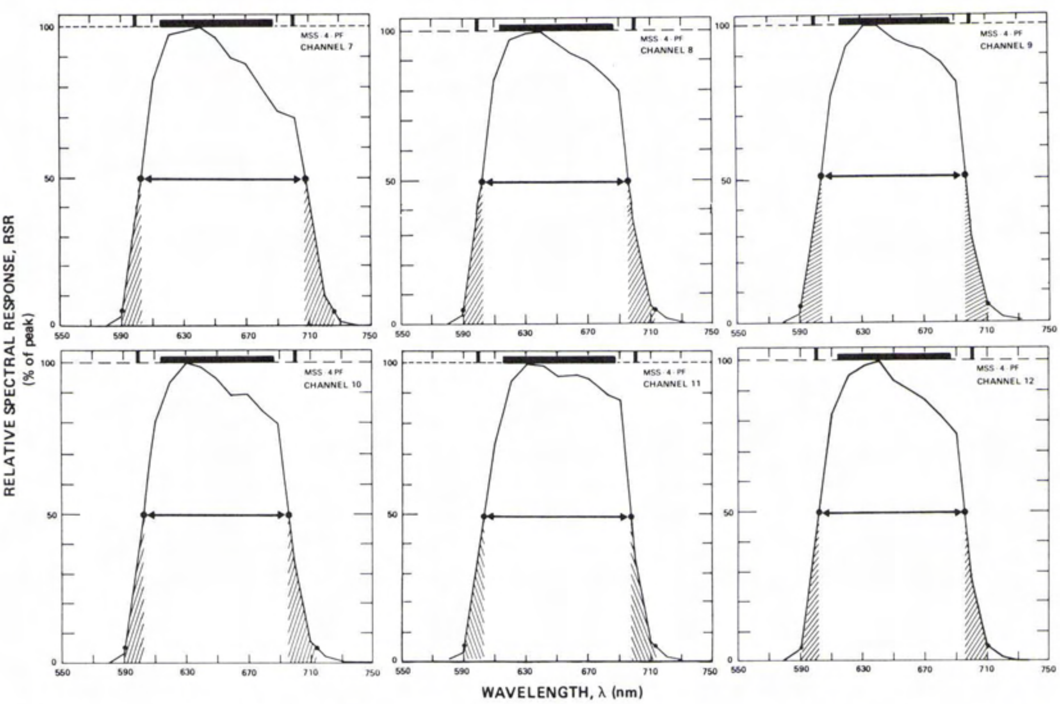

FIG. 3b. Protoflight model MSS (Landsat-4) relative spectral response curves from 1981 measurements (band 2).

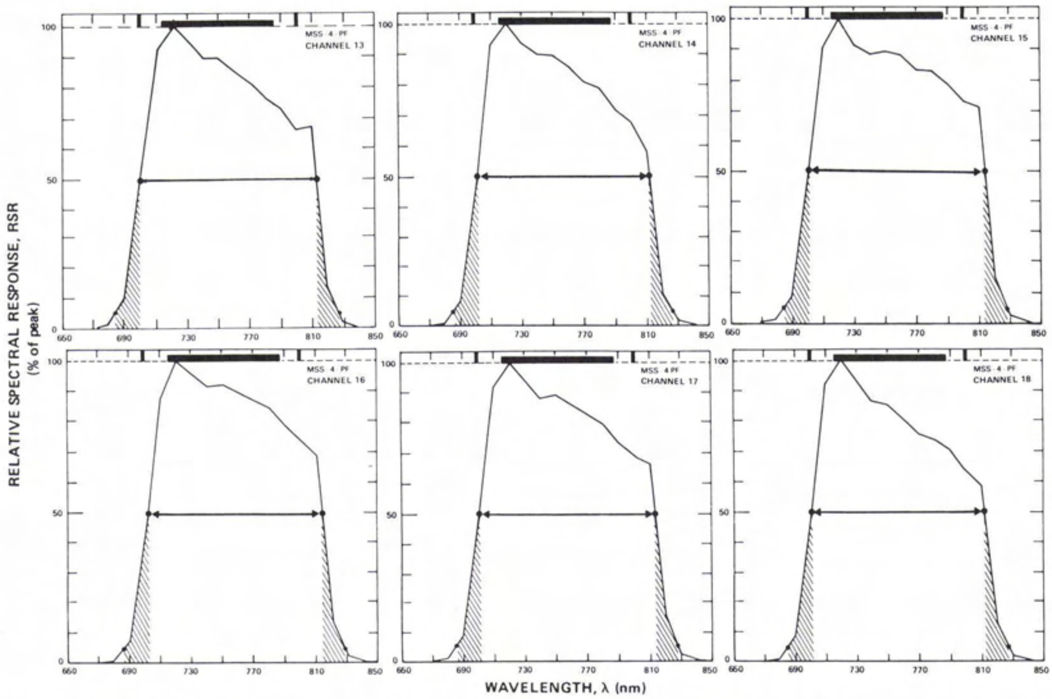

FIG. 3c. Protoflight model MSS (Landsat-4) relative spectral response curves from 1981 measurements (band 3).

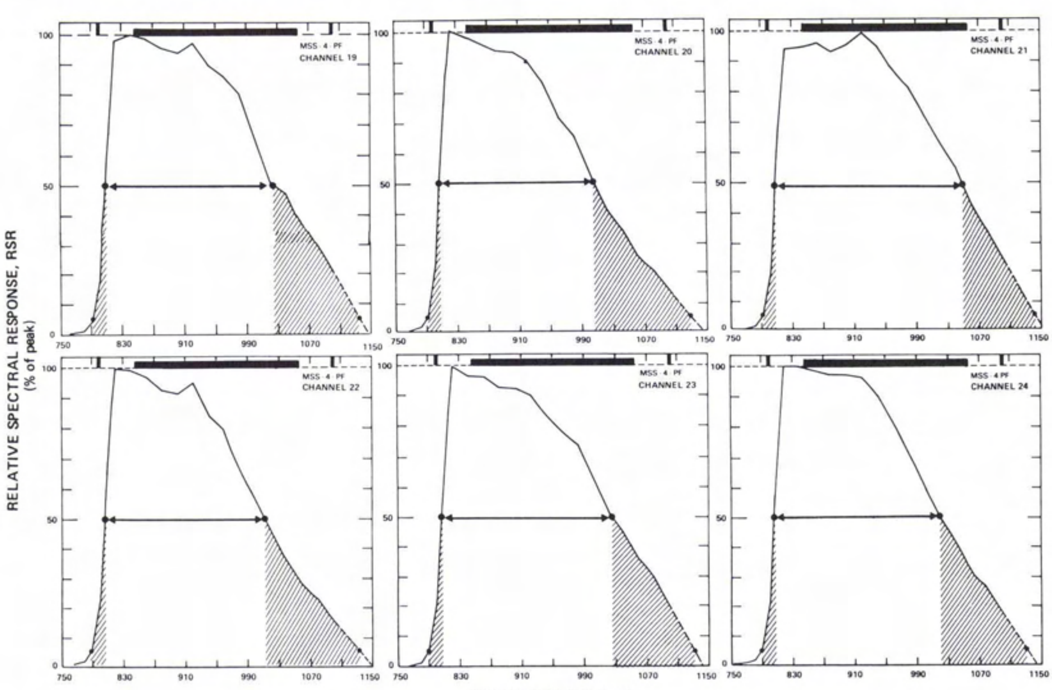

FIG. 3d. Protoflight model MSS (Landsat-4) relative spectral response curves from 1981 measurements (band 4). Response measured to 1100 nm; dashed line indicates extrapolated response.

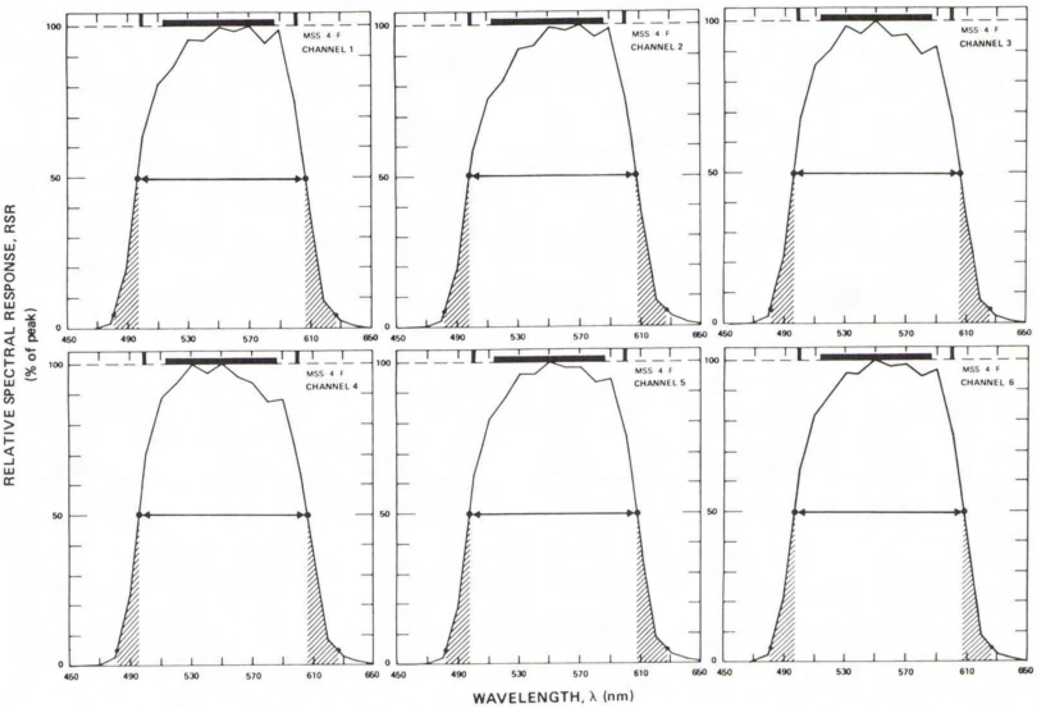

Fig. 4a. Flight model MSS (Landsat-4 backup) relative spectral response curves (band 1).

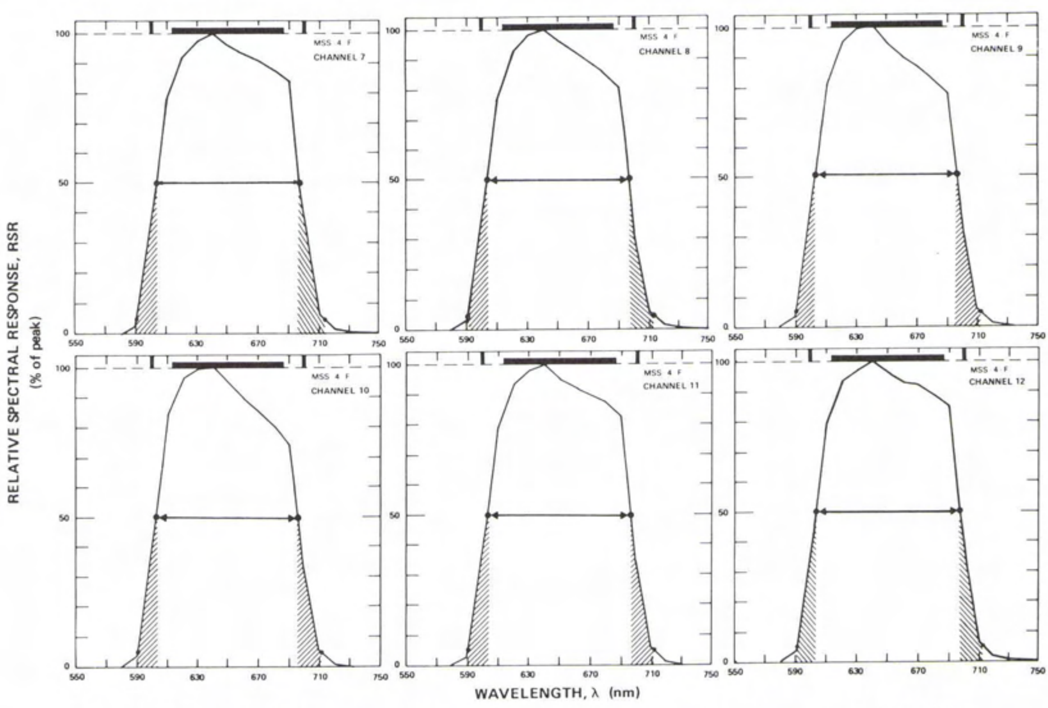

Fig. 4b. Flight model MSS (Landsat-4 backup) relative spectral response curves (band 2).

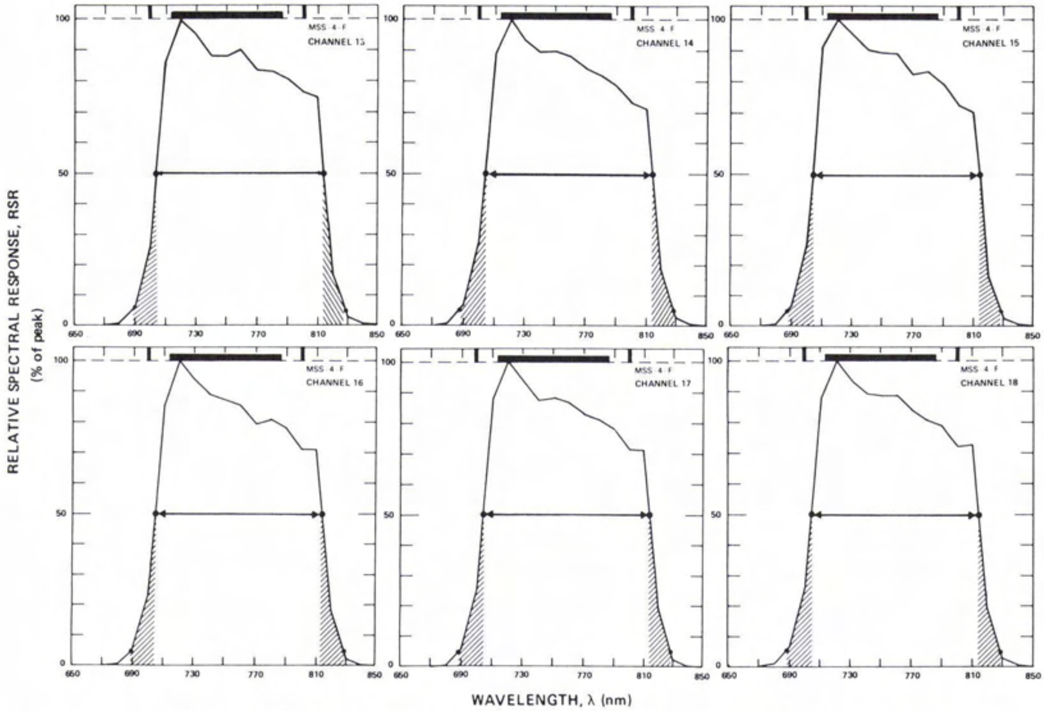

FIG. 4c. Flight model MSS (Landsat-4 backup) relative spectral response curves (band 3).

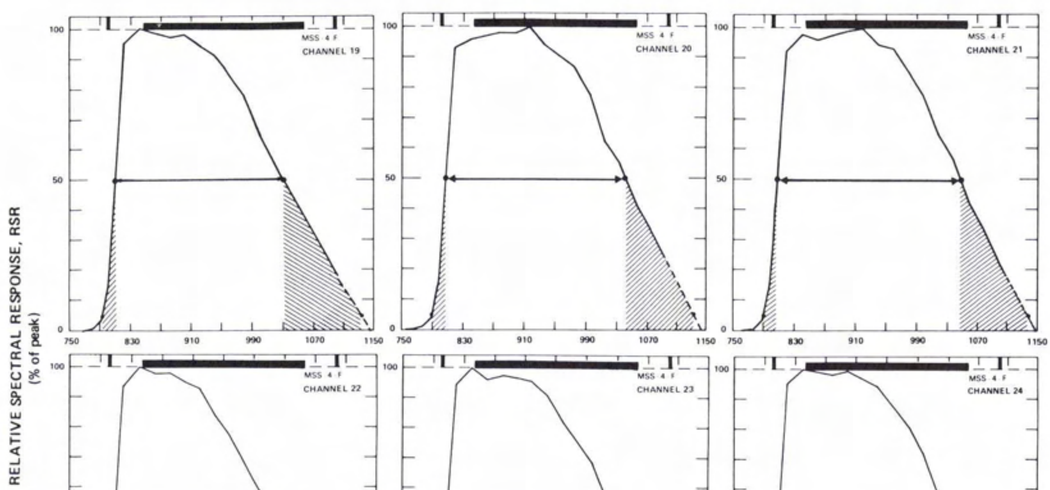

FIG. 4d. Flight model MSS (Landsat-4 backup) relative spectral response curves (band 4). Response measured to 1100 nm; dashed line indicates extrapolated response.

TABLE 2. SPECTRAL CHARACTERIZATION OF LANDSAT-4 MSS'S BY CHANNEL: BAND 1 (500 TO 600 NM)

Scanner	Channel	Band Edge (nm)		Width[a] (nm)	Slope Interval (nm)		Spectral Flatness	
		Lower	Upper		Lower	Upper	Positive	Negative
Protoflight	1	496	606	110	15	22	4.4	7.1[b]
	2	496	605	109	15	22	3.5	5.8[b]
	3	496	605	109	15	23	5.6[b]	9.2[b]
	4	495	604	109	15	24	6.0[b]	10.8[b]
	5	495	603	108	14	24	6.0[b]	13.1[b]
	6	495	606	110	15	22	4.8	7.8[b]
Flight	1	497	607	110	15	21	4.4	12.3[b]
	2	498	607	109	16	20	6.2[b]	16.8[b]
	3	496	606	110	15	20	5.3[b]	6.8[b]
	4	496	606	110	15	21	4.9	8.8[b]
	5	497	607	110	16	21	4.8	11.5[b]
	6	497	607	111	16	19	4.6	11.1[b]

[a] No filter specification.
[b] Fails to meet filter specifications.

lar, and the following comments apply to both scanners unless otherwise noted:

- Band 1—No anomalous channels; relative spectral responses meet all filter specifications except flatness (Table 2).
- Band 2—PF channel 7 upper-band edge is 12-nm higher than the average of the other PF channels and is statistically an outlier (Figure 5); responses meet all filter specifications except flatness (Table 3).
- Band 3—No anomalous channels; all channels are slightly wide (2 to 4 nm) to the long wavelength side; otherwise, responses meet filter specifications except flatness (Table 4).
- Band 4—No anomalous channels, but upper-band edge varies by as much as 42 nm, resulting in width variations of up to 20 percent; system response upper-half power points below filter specifications because of silicon photodiode detector response; response flatness considerably below filter specifications (Table 5).

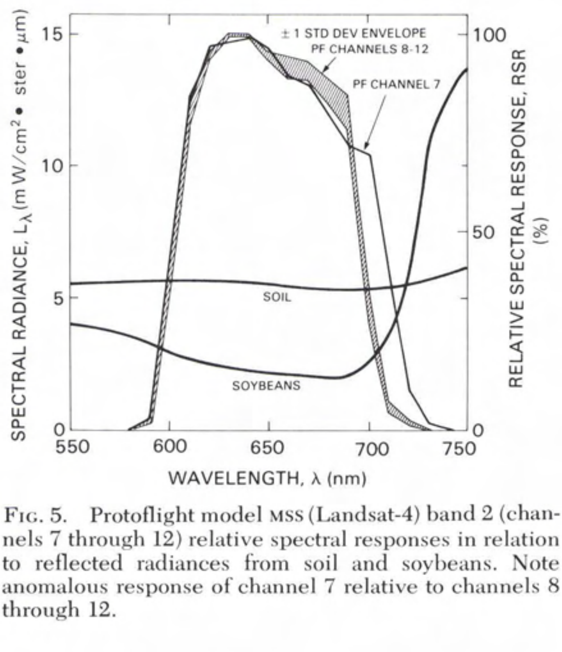

FIG. 5. Protoflight model MSS (Landsat-4) band 2 (channels 7 through 12) relative spectral responses in relation to reflected radiances from soil and soybeans. Note anomalous response of channel 7 relative to channels 8 through 12.

Besides the poorer uniformity of band 2 on the PF compared to the F as noted previously, the only other differences between the two scanners concerned the uniformity of the spectral flatness in bands 3 and 4, where the F is more uniform than the PF (Tables 6 through 9).

COMPARISON OF PF AND F SCANNER SPECTRAL CHARACTERISTICS WITH LANDSAT 1, 2, AND 3 SCANNERS

Meeting Filter Specifications. The relative spectral responses of previous MSS's failed to meet the filter specifications (Tables 6 through 9) in basically the same manner as those of the PF and F scanners (i.e., in the spectral flatness criteria). Although previous scanners met the band 3 upper-band edge specification, they occasionally failed elsewhere (e.g., the band 4 lower-band edge on the Landsat 3 MSS). Note that the filter specifications are only for comparison purposes; the overall response was not required to meet these specifications.

Anomalous Channels. Anomalous channels are not new to MSS scanners. Channel 6 (band 1) on the Landsat 1 (LS1) MSS was a statistical outlier on the basis of its spectral flatness (less flat). Channel 7 (band 2) on LS2 MSS was an outlier based on its upper-edge slope interval (wider).

Mean Characteristics. Because the PF and F

TABLE 3. SPECTRAL CHARACTERIZATION OF LANDSAT-4 MSS'S BY CHANNEL: BAND 2 (600 TO 700 NM)

Scanner	Channel	Band Edge (nm)		Width[a] (nm)	Slope Interval (nm)		Spectral Flatness	
		Lower	Upper		Lower	Upper	Positive	Negative
Protoflight	7	603	708*	105*	12	19	8.2[b]	17.2[b]
	8	602	696	94	12	16	6.4	11.6[b]
	9	603	696	92	12	14	6.6	11.0[b]
	10	603	696	94	12	18	7.8[b]	11.1[b]
	11	604	698	93	13	17	4.5	11.7[b]
	12	602	695	93	12	15	8.2[b]	14.5[b]
Flight	7	603	697	94	13	17	6.9	9.6[b]
	8	603	696	93	13	16	7.3	10.4[b]
	9	603	696	94	12	16	9.1[b]	13.3[b]
	10	602	696	93	12	14	9.1[b]	16.0[b]
	11	603	697	94	12	15	7.0	9.6[b]
	12	603	697	94	12	15	6.4	8.5[b]

[a] No filter specification.
[b] Fails to meet filter specification.
* Rejectable as outlier: $\alpha = 0.01$.

TABLE 4. SPECTRAL CHARACTERIZATION OF LANDSAT-4 MSS'S BY CHANNEL: BAND 3 (700 TO 800 NM)

Scanner	Channel	Band Edge (nm)		Width[a] (nm)	Slope Interval (nm)		Spectral Flatness	
		Lower	Upper		Lower	Upper	Positive	Negative
Protoflight	13	700	813[b]	113	16	14	13.7[b]	14.2[b]
	14	701	812[b]	110	16	15	11.6[b]	15.7[b]
	15	701	814[b]	113	15	14	12.9[b]	8.6[b]
	16	702	814[b]	111	15	14	7.8[b]	10.0[b]
	17	701	813[b]	112	15	15	13.0[b]	13.0[b]
	18	701	812[b]	111	15	16	18.5[b]	15.3[b]
Flight	13	704	814[b]	110	16	14	11.8[b]	8.3[b]
	14	704	814[b]	110	17	14	12.2[b]	10.3[b]
	15	704	814[b]	110	17	14	11.8[b]	9.5[b]
	16	704	814[b]	110	14	14	14.4[b]	9.6[b]
	17	704	814[b]	110	16	14	13.6[b]	9.7[b]
	18	704	814[b]	110	17	14	12.0[b]	10.4[b]

[a] No filter specification.
[b] Fails to meet filter specification.

TABLE 5. SPECTRAL CHARACTERIZATION OF LANDSAT-4 MSS'S BY CHANNEL: BAND 4 (800 TO 1100 NM)

Scanner	Channel	Band Edge (nm)		Width[a] (nm)	Slope Interval (nm)		Spectral Flatness	
		Lower	Upper		Lower	Upper[a]	Positive	Negative
Protoflight	19	808	1025	217	23	110	25.5[b]	48.5[b]
	20	808	1006	199	23	120	38.7[b]	62.2[b]
	21	808	1049	241	24	94	19.5[b]	44.8[b]
	22	807	1012	205	23	117	34.9[b]	59.5[b]
	23	807	1025	218	23	108	31.1[b]	50.2[b]
	24	807	1018	211	23	112	29.3[b]	56.7[b]
Flight	19	809	1030	221	23	104	24.0[b]	51.3[b]
	20	809	1048	239	23	92	17.6[b]	46.8[b]
	21	809	1047	238	23	93	16.9[b]	46.5[b]
	22	809	1014	206	23	119	33.4[b]	57.7[b]
	23	809	1034	236	23	103	24.9[b]	51.3[b]
	24	809	1040	231	22	98	21.1[b]	51.2[b]

[a] No filter specification.
[b] Fails to meet filter specification.

TABLE 6. BAND 1 (500 TO 600 NM) SPECTRAL CHARACTERIZATION BY MEANS AND STANDARD DEVIATIONS: MSS-1, 2, 3, PF AND F

	Scanner	Band Edge (nm) Lower	Band Edge (nm) Upper	Width[a] (nm)	Slope Interval (nm) Lower	Slope Interval (nm) Upper	Spectral Flatness Positive	Spectral Flatness Negative
Means	PF	495	605	109	15	23	5.1[b]	8.9[b]
	F	497	607	109	15	21	5.0	11.2[b]
	1*	501	599	98	15	27	7.1[b]	16.1[b]
	1**	499	597	98	15	27	6.1[b]	14.6[b]
	2	497	598	101	15	22	5.4[b]	14.1[b]
	3	497	593	96	16	22	5.4[b]	19.2[b]
Standard Deviations	PF	0.5	1.2	0.8	0.3	1.0	1.0	2.7
	F	0.8	0.8	0.5	0.6	0.7	0.6	3.4
	1*	6.5	4.1	3.5	1.6	5.6	2.4	6.4
	1**	5.3	3.0	3.5	1.8	5.4	0.4	5.8
	2	1.4	1.4	1.8	1.2	0.6	2.4	3.5
	3	3.7	2.5	3.8	3.2	3.4	1.5	7.8

* With outlier channel included.
** With outlier channel excluded.
[a] No filter specification.
[b] Fails to meet filter specification.
Boxes indicate characteristics where differences between PF or F and all previous scanners (1, 2, 3) were greater than differences between two sets of PF measurements.

scanners were essentially the same in terms of mean spectral response characteristics (Tables 6 through 9), they had a common set of differences from the LS1, LS2, and LS3 scanners. Because the characteristics of the LS1, LS2, and LS3 scanners were not consistent, the PF/F scanners differed from each one individually in dissimilar ways. The PF and F were different from all three previous scanners in the following ways:

- Band 1—Upper-band edge higher (7 to 14 nm); (Table 6)
  Bandwidth wider (8 to 13 nm) (Figure 6)
- Band 2—Upper-band edge lower (3 to 13 nm); (Table 7)
  Upper-slope interval narrower (10 to 16 nm) (Figure 7)
- Band 3—Lower-band edge higher (4 to 11 nm);
  Upper-band edge higher (11 to 21 nm); (Table 8)
  Upper-slope interval narrower (17 to 21 nm). (Figure 8)

In band 4 (Table 9, Figure 9), a number of large differences were apparent between the PF/F scanners and previous Landsats, particularly in regard to upper-band edge, bandwidth, and spectral flatness. The large magnitudes of these differences are believed to result from differences in test conditions or test equipment when the tests were conducted on the different scanners (Appendix C). This belief is based on the lesser differences between the PF model June 1980 measurements and the previous scanners than between the June 1981 PF measurements and the previous scanners (Figure 10).

Within-Band Variation. Previous Landsat MSS's displayed quite a range of within-band variability (Tables 6 through 9) in their spectral characteristics. For example, a factor of 4 difference in the standard deviation for a given characteristic between the best previous MSS (least variable) and the worst MSS (most variable) was not uncommon. Thus, in very few cases did the Landsat-4 MSS's differ from (fall outside the range of)

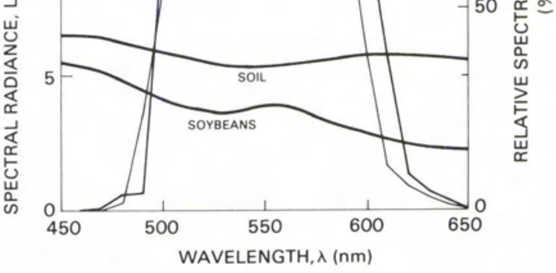

FIG. 6. MSS band 1 relative spectral response averages for Landsat-4 (PF, F) and for previous Landsats in relation to reflected radiances from soil and soybeans.

TABLE 7. BAND 2 (600 TO 700 NM) SPECTRAL CHARACTERIZATION BY MEANS AND STANDARD DEVIATIONS: MSS-1, 2, 3 PF AND F

	Scanner	Band Edge (nm)		Width[a] (nm)	Slope Interval (nm)		Spectral Flatness	
		Lower	Upper		Lower	Upper	Positive	Negative
Means	PF*	603	698	95	12	16	7.0	12.9[b]
	PF**	603	696	93	12	16	6.7	12.0[b]
	F	603	697	94	12	15	7.6[b]	11.1[b]
	1	603	701	97	15	26	9.0[b]	13.3[b]
	2*	607	710	103	14	30	7.9[b]	18.0[b]
	2**	607	710	103	14	29	7.8[b]	16.8[b]
	3	606	705	100	1	31	7.2	17.2[b]
Standard Deviations	PF*	0.7	4.7	4.8	0.5	1.9	1.4	2.5
	PF**	0.8	0.8	0.6	0.5	1.4	1.5	1.4
	F	0.4	0.6	0.5	0.4	0.9	1.2	3.0
	1	3.5	2.2	2.8	1.7	3.4	3.4	2.8
	2*	0.6	0.8	1.0	1.2	3.6	1.1	4.5
	2**	0.6	0.9	1.1	1.2	1.0	1.2	3.8
	3	0.9	1.2	0.8	0.8	2.0	2.0	4.8

* With outlier channel included.
** With outlier channel excluded.
[a] No filter specification.
[b] Fails to meet filter specification.
Boxes indicate characteristics where differences between PF or F and all previous scanners (1, 2, 3) were greater than differences between two sets of PF measurements.

all three previous scanners. However, for all spectral characteristics except those related to the band 4 upper-band edge (PF and F) and the band 2 upper-band edge (PF), the Landsat-4 MSS's were as uniform as the most uniform of the previous MSS's. The band 4 upper-band edge (PF and F), as well as the negative spectral flatness (PF), were less uniform than that of any previous MSS (Table 9), as was the band 2 upper-band edge (PF) and its related width (Table 7).

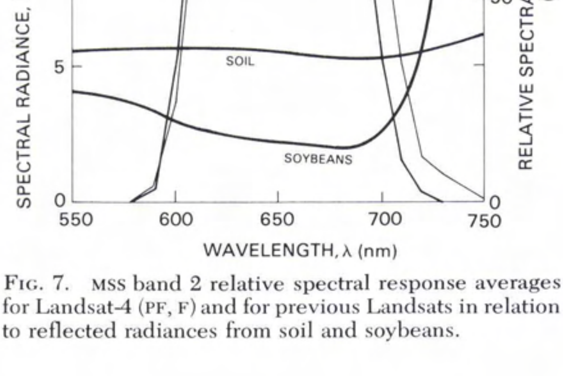

FIG. 7. MSS band 2 relative spectral response averages for Landsat-4 (PF, F) and for previous Landsats in relation to reflected radiances from soil and soybeans.

SIMULATED MSS BANDS MEAN OUTPUTS TO SOYBEANS AND SOILS: PF, F, LS1, LS2, AND LS3

PF Versus F. Because the PF and F have essentially the same mean spectral characteristics, they gave essentially the same simulated outputs to soil and soybeans targets (Table 10). The only difference occurred in band 3, where the F output to soybeans was higher than the PF. This difference resulted from the slightly shifted response of the F(704 to 814 nm), compared to the PF(701 to 813 nm), combined with the rapid increase in soybeans reflectance between 690 and 770 nm (Figure 8).

PF/F Versus LS1, LS2, and LS3. For the soybean target, differences in output between the PF and F scanners and previous scanners were apparent for bands 2, 3, and 4. Band 2 and 4 outputs were lower and band 3 output was higher than that for previous Landsats. The band 2 output was lower because the upper-band edge was lower than that of previous Landsats and because of the rapid increase in soybean reflected radiance from 690 to 770 nm (Figure 7). A contributing factor was the steeper upper slope of the PF and F. The elevated band 3 output resulted from the band being wider and shifted to longer wavelengths relative to previous MSS's. Thus, the proportion of the near-infrared high reflectance plateau of

TABLE 8. BAND 3 (700 TO 800 NM) SPECTRAL CHARACTERIZATION BY MEANS AND STANDARD DEVIATIONS: MSS-1, 2, 3, PF AND F

	Scanner	Band Edge (nm) Lower	Band Edge (nm) Upper	Width[a] (nm)	Slope Interval (nm) Lower	Slope Interval (nm) Upper	Spectral Flatness Positive	Spectral Flatness Negative
Means	PF	701	813[b]	112	15	15	13.2[b]	12.8[b]
	F	704	814[b]	110	16	14	12.6[b]	9.6[b]
	1	694	800	105	19	35	7.2[b]	7.4[b]
	2	697	802	106	16	34	8.4[b]	7.9[b]
	3	693	793	100	19	32	9.9[b]	22.2[b]
Standard Deviations	PF	0.7	0.9	1.1	0.3	0.5	2.9*	2.9*
	F	0.3	0.2	0.3	1.0	0.3	1.1*	0.8*
	1	0.9	1.0	0.9	2.0	3.8	3.2	2.9
	2	1.1	2.3	2.1	0.6	2.7	3.0	1.9
	3	1.8	1.6	0.8	1.4	1.1	2.7	3.4

* PF, F difference exceeds difference between two sets of PF measurements.
[a] No filter specification.
[b] Fails to meet filter specification.
Boxes indicate characteristics where differences between PF or F and all previous scanners (1, 2, 3) were greater than differences between two sets of PF measurements.

the vegetation included in the band as increased (Figure 7), which increased the output in the band.

The outputs in band 4 to soybeans on the PF and F models relative to LS1, LS2, and LS3 scanners were depressed because the response of the PF and F apparently extended to longer wavelengths and the radiance reflected from soybeans decreased with increasing wavelength (Figure 9). As mentioned earlier, because the extended responses in the PF and F are believed to be mainly spurious, the extent of depression of the output values is overestimated.

For the spectrally flatter soil target, the differences between scanner characteristics did not result in differences in mean outputs between the PF/F and the LS1, LS2, and LS3 scanners, except for the apparent difference in band 4.

WITHIN-BAND VARIATION IN MSS OUTPUTS TO SOYBEANS AND SOIL: PF, F, LS1, LS2, AND LS3

The within-band sensor output differences (Table 11) were larger for the PF than the F scanner in bands 2, 3, and 4 for the soybean target. The larger difference in band 2 of the PF compared to the F resulted from the anomalous channel on the PF with an upper-band edge of 708 nm, as opposed to the 696-nm norm for the rest of the band 2 channels. The band 3 and 4 differences were a result of the poorer uniformity of the PF than the F in spectral response, particularly flatness. For the soil target, differences between the PF and F in within-band sensor output differences were negligible.

The within-band sensor output differences of the PF and F for the soybean target were equal to or better than those of the most uniform previous Landsat, except for PF band 2 and PF/F band 4 (Table 11). The maximum difference in PF band 2 was of the same order as the difference observed in the Landsat 2 MSS, which was the worst of the previous MSS's in that band. In band 4, the maximum within-band difference for the F model was of the same order as the Landsat 3

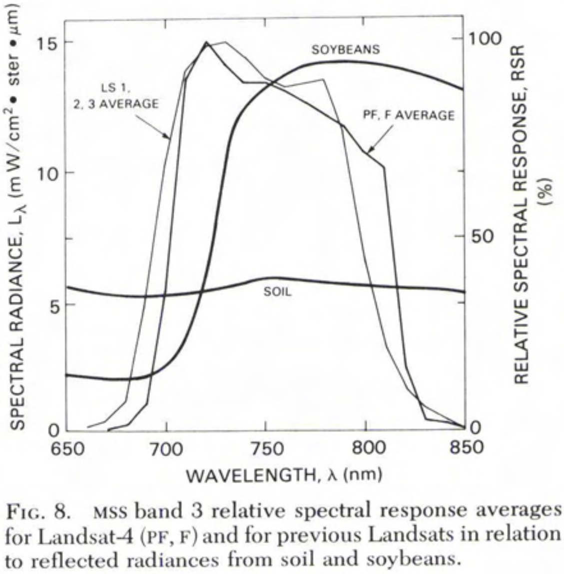

FIG. 8. MSS band 3 relative spectral response averages for Landsat-4 (PF, F) and for previous Landsats in relation to reflected radiances from soil and soybeans.

TABLE 9. BAND 4 (800 TO 1100 NM) SPECTRAL CHARACTERIZATION BY MEANS AND STANDARD DEVIATIONS: MSS-1, 2, 3, PF AND F

	Scanner	Band Edge (nm) Lower	Band Edge (nm) Upper	Width[a] (nm)	Slope Interval (nm) Lower	Slope Interval (nm) Upper[a]	Spectral Flatness Positive	Spectral Flatness Negative
Means	PF	808	1023	215	23	110	29.8[b]	53.7[b]
	F	809	[1036]	[227]	23	101	[23.0[b]]	50.8[b]
	1	810	989	179	22	120	46.0[b]	74.5[b]
	2	807	990	183	23	118	45.4[b]	75.9[b]
	3	812[b]	979	167	24	108	56.4[b]	80.7[b]
Standard Deviations	PF	0.5	[14.9]	[14.6]	0.2	9.2	6.8	[6.8*]
	F	0.1	[12.5]	[12.5]	0.4	9.9	6.0	4.1*
	1	1.2	3.5	3.7	2.1	7.2	2.3	3.1
	2	2.0	4.0	5.3	0.8	2.7	4.7	1.1
	3	0.9	7.9	7.6	1.0	3.0	11.7	2.4

* PF, F difference exceeds difference between two sets of PF measurements.
Boxes indicate characteristics where differences between PF or F and all previous scanners (1, 2, 3) were greater than differences between two sets of PF measurements.
[a] No filter specification.
[b] Fails to meet filter specification.

MSS, which was the worst of previous MSS's; the PF was somewhat worse.

The band 4 PF and F maximum within-band output differences to soil were not larger than those for previous Landsats by the criteria used. In terms of percentage of mean output, however, these differences were similar between soil and soybean targets. This indicates that the striping in band 4 would be primarily nontarget-dependent and would therefore be potentially removable.

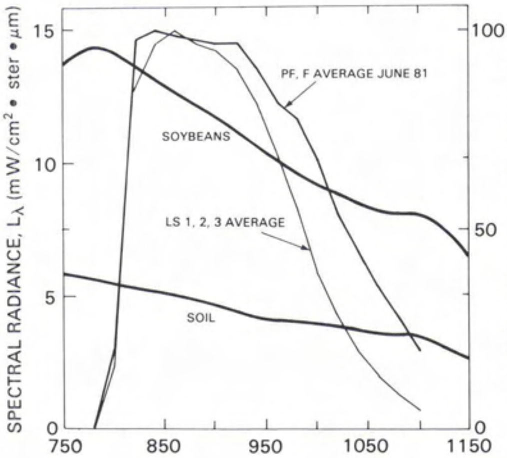

FIG. 9. MSS band 4 relative spectral response averages for Landsat-4 (PF, F) and for previous Landsats in relation to reflected radiances from soil and soybeans (atmospheric water absorption not simulated).

COMPARISON OF SIMULATED DATA TO REAL LANDSAT DATA

The simulated Landsat data were compared with actual Landsat 2 data collected under conditions similar to those simulated (37° solar zenith angle, moderately clear, east-coast United States summer day) to determine if the simulated data were reasonable (Table 12). Except for band 4,

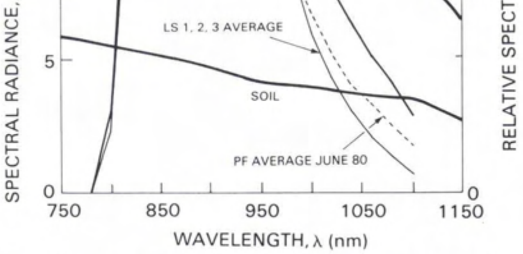

FIG. 10. MSS band 4 relative spectral responses for: (1) Landsat-4 PF measured June 1980, (2) Landsat-4 PF measured June 1981, and (3) Landsats 1, 2, and 3 average in relation to reflected radiances from soil and soybeans (atmospheric water absorption not simulated). Note apparent large change in PF response above 900 nm between June 1980 and June 1981.

TABLE 10. SIMULATED MSS BAND MEAN OUTPUTS TO SOYBEAN AND SOIL TARGETS: MSS-1, 2, 3, PF AND F

Target	Sensor System	Band 1[b]	Band 2[b]	Band 3[b]	Band 4[b]
		Means[a] (Digital MSS Counts)			
Soybeans	LS4-PF	19.36	14.89 (14.76)[c]	80.82*	45.80
	LS4-F	19.25	14.72	82.81*	45.39
	LS1	19.46 (19.55)[c]	15.43	76.95	47.14
	LS2	19.58	16.24 (16.13)[c]	78.58	47.24
	LS3	19.77	15.36	73.93	47.55
Soil	LS4-PF	28.39	34.75[d]	41.02	18.61
	LS4-F	28.39	34.75	41.05	18.48
	LS1	28.32[d]	34.73	41.04	19.02
	LS2	28.34	34.66[d]	41.05	19.07
	LS3	28.33	34.66	41.10	19.15

[a] At satellite sensor response, NADIR—looking for 40° solar zenith angle and 20 km visibility; units are simulated non-truncated MSS digital counts with maximum specified radiance scaled to 127.99 for bands 1, 2, 3 and 63.99 for band 4.
[b] Landsat-4 bands 1, 2, 3 and 4 correspond to bands 4, 5, 6 and 7, respectively on previous landsats.
[c] Mean in parentheses is with outlier channel excluded.
[d] Exclusion of outlier did not change band mean.
* PF, F difference exceeds: (1) difference between simulations run with each set of PF measurements separately and (2) 0.30 digital counts.
Boxes indicate bands where output differences between PF or F and all previous scanners (1, 2, 3) exceed: (1) and (2) as above.

TABLE 11. SIMULATED MSS OUTPUT DIFFERENCES BETWEEN CHANNELS WITHIN A BAND (MAXIMUM-MINIMUM) RESULTANT FROM SPECTRAL DIFFERENCES BETWEEN CHANNELS: MSS-1, 2, 3, PF AND F

Target	Sensor	Digital Counts Band 1	Band 2	Band 3	Band 4	Percent Band 1	Band 2	Band 3	Band 4
Soybeans	LS4-PF	0.11	0.91*	2.23*	1.43*	0.6	6.2*	2.8*	3.1*
	LS4-F	0.17	0.10*	0.78*	1.04*	0.9	0.7*	0.9*	2.3*
	LS1	0.75	0.12	2.39	0.63	3.9	0.8	3.1	1.3
	LS2	0.16	0.77	3.63	0.39	0.8	4.8	4.6	0.8
	LS3	0.30	0.16	4.01	0.80	1.5	1.0	5.4	1.7
Soil	LS4-PF	0.03	0.07	0.10	0.46	0.1	0.2	0.2	2.5
	LS4-F	0.01	0.05	0.02	0.32	0.1	0.2	0.1	1.8
	LS1	0.10	0.09	0.04	0.21	0.3	0.3	0.1	1.1
	LS2	0.05	0.03	0.06	0.12	0.2	0.1	0.2	0.6
	LS3	0.07	0.09	0.13	0.26	0.2	0.3	0.3	1.4

* PF, F difference exceeds: (1) difference between simulations run with each set of PF measurements separately and (2) 0.03 digital counts.
Boxes indicate bands where output differences between PF or F and all previous scanners exceed (1) and (2) as above; this can represent either better or poorer performance.

TABLE 12. ILLUSTRATIVE LANDSAT-2 MSS OBSERVATIONS* FOR SELECTED TARGETS FOR COMPARISON TO SIMULATED RESULTS†: MEANS AND STANDARD DEVIATIONS

Test Site Category	Number of Pixels	Band 1 [4]	Band 2 [5]	Band 3 [6]	Band 4 [7]
		Means (Standard Deviations) (Digital MSS Counts)			
Soybeans	15	19.8 (1.4)	16.9 (1.1)	77.3 (7.3)	41.1 (3.8)
Oats (Cut)	24	23.6 (2.0)	27.2 (2.7)	40.8 (2.5)	18.4 (1.2)
Wheat (Cut)	46	21.3 (2.5)	25.6 (2.7)	38.6 (4.9)	17.0 (2.8)

* Scene 82905145015 (Path 17 Row 30).
July 15, 1977 Nominal SZA—38°.
Center field pixels, Central New York State.
† In ground processing of actual MSS data, after decompression, the MSS data is rescaled using sensor specific saturation radiances and offsets. As such the simulated outputs may not be strictly comparable to calibrated actual MSS data.

the outputs of the simulated and actual soybean targets were in good agreement. The only targets characterized in the Landsat 2 scene that resembled bare soil were harvested wheat and oats. As might be expected, larger differences between simulated and actual were observed given the difference in the targets themselves. As noted earlier, the high values of simulated band 4, particularly for soybeans, probably resulted from the lack of modeling of atmospheric water absorption.

Discussion

Differences in mean responses between scanners

The comparisons performed to determine how the PF and F differ from previous scanners in mean responses and outputs essentially indicate the ways in which the PF and F fall outside the range exhibited by the LS1, LS2, and LS3 MSS's. Note that if these comparisons were done with LS3 MSS's as compared to LS1 and LS2 MSS's, for example, a similar number of differences would be indicated. Thus, although the PF and F are different from previous scanners in selected ways, differences of this level are not unexpected or unprecedented, but are typical of the differences between existing scanners. No greater problems are anticipated in comparing data from the LS4 scanners (e.g., as in a change detection algorithm) than between LS3 MSS and LS2 MSS data. In addition, it is encouraging that the PF and F scanners are so similar in response.

Differences in within-band variation between scanners

Target-dependent output differences between channels place a fundamental limit on the ability to discriminate between targets, producing "spectral striping." Exclusive of band 4, where the apparent output differences appear to be nontarget-dependent, the PF band 2 is the only case in which one of the LS4 scanners is poor in "spectral striping" potential for the targets evaluated. This "spectral striping," simulated to be 6.2 percent for a soybean target, occurs in a band that is important for vegetation discrimination. This may have an impact on data utility for this type of application.

Previous studies have assessed the magnitude of the spectral striping problem for the MSS's on Landsats 1 through 3 in a manner somewhat similar to this study (Slater, 1979; Duggin and Ellis, 1980). Except for band 4, the relative magnitudes of the within-band stripings between scanners are similar between studies (e.g., Landsat 1 is the most variable in band 1, Landsat 2 is the most variable in band 2, and Landsat 3 is the most variable in band 3).

However, the relative magnitudes of the striping as simulated here are different from those of previous studies because these studies

- Assumed constant irradiance across the bandpasses,
- Did not add a path radiance (haze) to the simulation, and
- Used different reflectance spectra for the simulations.

The first factor is primarily of concern in the wider bandpass of band 4 and tends to induce striping in this band. This results in the larger (0.8 to 1.7 percent) maximum intraband striping for this band in this study when compared to the work of Duggin and Ellis (0 to 0.6 percent). Because this is not target-dependent striping, however, it is potentially removable.

The second factor has the largest effect on bands 1 and 2 because the addition of a spectrally slowly varying haze reduces the relative magnitude of the interline striping. For example, using the data of Slater (1979), the percent difference in response between channels 7 and 8 on the Landsat 2 MSS is reduced from 14 percent when using reflectance to about 8 percent when using simulated radiances, including path radiance. The amount of this reduction depends, of course, on the level of haze.

The third factor is most important in band 2. A significant amount of variation occurs in the wavelength of onset and the steepness of the reflectance slope of vegetated targets in the wavelength interval of 690 to 800 nanometres. The spectra of an orange-tree leaf used by Slater (1979) nearly reaches its maximum reflectance at 730 nm, whereas the soybean canopy spectra used here does not reach the same reflectance until 770 nanometres. This accounts for the 8-percent difference when using Slater's data as opposed to 4.5 percent when using the data of this study.

Summary and Conclusions

The Landsat-4 PF and F scanners were essentially identical in mean spectral response. Spectral differences between the PF and F model and previous scanners resulted in some differences between the simulated outputs to targets. The principal differences that affected the simulated sensor outputs from soybeans and/or soil were

- A lower upper-band edge and a narrower upper-slope interval on PF and F in band 2, resulting in lower sensor output from a soybean target than that of previous Landsat MSS's; and
- A higher lower-band edge and a higher upper-band edge on PF and F in band 3, resulting in

higher sensor outputs from soybean targets than those of previous Landsats.

A higher upper-band edge and a wider bandwidth on PF and F in band 1 did not affect the outputs from soil or soybean targets. The differences between PF, F, and previous scanners were usually small (i.e., differences between the PF or F and the most similar previous MSS were about the same as differences between previous MSS's). In general, therefore, these differences should not affect data utility more severely than the variability between prior Landsat MSS's.

One anomalous channel in the red band (2) on the PF scanner, with an upper-band edge 12-nm higher than those of the other channels in the band, has the greatest potential effect on the utility of Landsat-4 MSS data. This characteristic resulted in a potential within-band striping in simulated output to a vegetated target in band 2 of 6.2 percent, which was about the same as the highest observed for previous Landsat MSS's (5.4 percent). In band 4 on the PF and F scanners, the upper-band edge was also more variable than those of previous MSS's. Otherwise, the PF and F scanners were generally more uniform within bands than previous scanners.

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Appendix A
Relative Spectral Response Measurement Procedure

The relative spectral responses of the protoflight and flight model MSS's were measured at the Santa Barbara Research Center. The protoflight model RSR was measured in June 1980 and June 1981. The flight model RSR was first measured in March 1981; then the fiber optics assembly was replaced, and it was remeasured in June 1981. The earlier flight model measurements are considered inapplicable due to this optical change.

The instrumentation used to measure the relative spectral response of an MSS consisted of the following:

- A tungsten-halogen light source
- A plane diffraction grating monochromator
- Two beam steering mirrors
- A calibrated reference silicon photo diode
- The MSS collimator

White light from the tungsten-halogen source impinged on the entrance slit of the monochromator. Within the monochromator dispersion was accomplished by means of a plane diffraction grating equipped with sine bar motion. A counter on the drive screw read wavelength directly in nanometres. The entrance and exit slits were adjusted to obtain 4-nanometre spectral resolution at any particular wavelength setting. Light exiting the monochromator impinged on a fiber optic bundle which transferred the light to the focal plane of the MSS collimator. The two beam steering mirrors located at this point chopped the light, alternately focusing it on the reference detector and letting it pass into the collimator. The collimator, optically aligned with the MSS, passed the light to the MSS, where the slit image completely overfilled all 24 channels simultaneously. The outputs from the reference detector and the MSS detectors were sampled at 10-nm intervals from 450 to 800 nm and 20-nm intervals from 800 to 1100 nm. The ratio of these two outputs, normalized to 100 percent maximum for each channel, was the relative spectral response.

Appendix B
Protoflight and Flight Model Filter Characteristics

With the exception of the upper-band edge of band 4 (800 to 1100 nm), which is determined by the silicon photodiode response, the spectral filters are the primary components that determine the spectral response of the various channels. Tables B-1 and B-2 list the spectral response (transmission) characteristics of the filters only. These data were computed from curves supplied by Hughes Aircraft Company (unpublished data, 1981) and subsequently digitized at 10-nm intervals for bands 1 through 3 and 20-nm intervals for band 4.

Technically, most of the band 1 filters, having negative deviations greater than 5 percent, failed the flatness criteria. However, because the flatness criteria are considered to be met if the sum of the positive and negative deviations does not exceed 10 percent, they do pass. A similar situation exists for band 2; however, the sum of the positive and negative deviations typically slightly exceeds the specified 15 percent. Otherwise the filter specifications were met.

When compared to the total system response, the band edges, widths, and slope intervals of the filters compare favorably for bands 1, 2, and 4, being generally within 2 nanometres of each other. For band 3, the measured filter band edges are lower than the system response band edges. The upper-band edge of the system response is generally 10-nm greater than the filters, except for three channels, the difference of which is 5 to 6 nanometres. Smaller differences with the same pattern exist for the lower-band edge. One unexplained observation is that filters 13, 15, and 18 on the F model, which are offset 4 nm relative to the other filters, do not show the same pattern for the total system response.

There are several possible explanations for this discrepancy. One is that there was a difference in the spectral calibration of the spectrometer used to measure the filter transmission coefficients and the monochromator to measure the relative spectral responses (i.e., one or both were spectrally improperly calibrated). This possibility appears unlikely because the band 4 filters, which were measured with the same spectrometer at approximately the same time as the band 3 filters and whose lower-band edge corresponds approximately with the upper-band edge for band 3, show little difference in their lower-band edge when compared to the relative system response lower-band edge (Figure B-1).

A second possibility is that the band 3 filters have been changing in their bandpass with time. The spectral characteristics of all the band 3 filters except for F 13, 15, and 18 were measured in December 1978. F 13, 15, and 18 were measured in November 1979. The relative spectral responses reported herein were measured in June 1981.

TABLE B-1. MSS FILTER SPECTRAL CHARACTERIZATION BY CHANNEL PF FOR LANDSAT-4

Band	Channel	Band Edge (nm)		Width* (nm)	Slope Interval (nm)		Spectral Flatness		Maximum Transmission (%)
		Lower	Upper		Lower	Upper	Positive	Negative	
1	1	495	607	112	14	21	2.5	5.8†	93
	2	495	605	110	15	21	2.5	5.8†	93
	3	494	605	111	14	21	2.1	5.6†	93
	4	494	606	111	14	21	2.1	5.6†	93
	5	494	605	112	13	21	2.1	5.0	93
	6	493	604	111	13	22	1.7	4.9	93
2	7	603	710	107	12	16	3.2	13.1†	95
	8	601	697	96	13	16	3.3	12.1†	94
	9	602	697	95	13	16	3.3	13.8†	94
	10	602	698	96	12	17	2.8	13.1†	94
	11	602	697	95	12	18	3.3	13.2†	94
	12	602	697	95	13	17	3.3	13.8†	94
3	13	696	804	107	14	14	1.5	2.7	96
	14	697	804	107	15	13	1.4	2.9	96
	15	696	804	108	14	13	1.8	2.4	96
	16	697	804	107	15	13	1.1	2.2	94
	17	697	804	107	15	13	1.3	2.8	98
	18	697	804	108	14	13	2.1	3.1	98
4	19	806	—	—	24	—	2.4	3.0	96
	20	806	—	—	24	—	2.0	3.3	96
	21	806	—	—	24	—	1.8	4.6	96
	22	806	—	—	24	—	1.8	3.5	96
	23	806	—	—	24	—	2.4	2.9	96
	24	806	—	—	24	—	1.6	3.7	96

* No filter specification.
† Fails to meet filter specification.

TABLE B-2. MSS FILTER SPECTRAL CHARACTERIZATION BY CHANNEL: F FOR LANDSAT-4 BACKUP

Band	Channel	Band Edge (nm)		Width* (nm)	Slope Interval (nm)		Spectral Flatness		Maximum Transmission (%)
		Lower	Upper		Lower	Upper	Positive	Negative	
1	1	495	606	111	16	23	2.2	5.4†	94
	2	494	607	112	15	20	2.4	5.8†	93
	3	494	605	111	14	23	2.3	4.2	94
	4	494	605	111	14	24	3.6	5.8†	94
	5	495	605	111	14	21	2.6	5.7†	93
	6	494	606	112	15	21	2.1	5.6†	93
2	7	602	696	95	11	14	2.7	12.1†	94
	8	601	696	96	10	14	3.2	13.3†	94
	9	601	697	95	11	14	3.0	12.9†	94
	10	601	696	94	11	14	3.4	12.9†	95
	11	601	696	95	11	15	2.6	12.1†	94
	12	601	696	95	11	14	2.9	13.0†	94
3	13	701	808	108	17	12	2.1	2.1	98
	14	697	804	107	15	13	1.6	1.5	98
	15	701	808	107	17	12	1.3	1.8	96
	16	698	804	106	15	13	1.8	2.4	97
	17	698	804	106	16	13	2.0	2.2	97
	18	701	809	108	16	14	1.5	2.7	98
4	19	808	—	—	24	—	2.3	4.1	96
	20	806	—	—	24	—	2.1	4.2	97
	21	807	—	—	25	—	2.7	3.6	97
	22	808	—	—	24	—	2.0	4.4	95
	23	808	—	—	24	—	3.8	4.8	97
	24	808	—	—	24	—	3.2	5.4	96

* No filter specification.
† Fails to meet filter specification.

When plotted versus time, a monotonic change is suggested (Figure B-1). When data from the first relative spectral response runs on the PF are included (June 1980), the curve shows a leveling-off trend. This suggests that the filters ceased to change after they were incorporated into the scanner. One explanation is that one or several layers of the many-layered interference filters were disturbed during storage or handling. The adsorption of water by interstitial voids or structural changes in the layers are possibilities. This multilayered structure principally determines the upper-band edge, whereas a color absorption filter primarily determines the lower-band edge. Thus, a disturbance to the interference layer structure would more likely affect the upper-band edge, as was observed (Yuh, private communication).

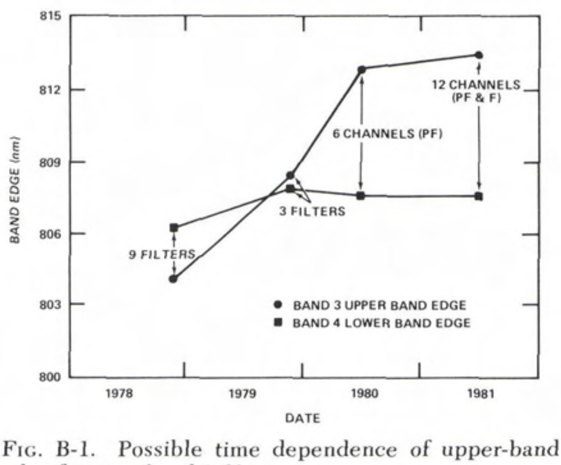

FIG. B-1. Possible time dependence of upper-band edge for MSS-4 band 3 filters.

When expressed as the sum of the positive and negative components, the spectral flatness criteria are always lower for the filters than for the entire system. This indicates that the principal effect of the detectors and optics is to degrade the flatness of the spectral response.

APPENDIX C
REPRODUCIBILITY OF RELATIVE SPECTRAL RESPONSE MEASUREMENTS

Only for the PF scanner was more than one set of relative spectral response (RSR) measurements available for the same unaltered scanner. The second set was collected in June 1980 (Table C-1), a year before the RSR measurements presented in the main text were acquired. The differences between the two sets of RSR measurements resulted from the composite effects of (1) the stability of the alignment and calibration of the test equipment used to measure RSR, (2) the stability of the scanner

TABLE C-1. MSS SPECTRAL CHARACTERIZATION BY CHANNEL: PF FOR LANDSAT-4 (JUNE 1980)

	Band Edge (nm)			Slope Interval (nm)		Spectral Flatness (%)	
Channel	Lower	Upper	Width* (nm)	Lower	Upper	Positive	Negative
1	498	607	110	17	22	10.6†	13.8†
2	497	606	109	17	22	9.7†	16.1†
3	498	606	109	16	21	9.1†	13.8†
4	497	607	110	17	21	7.5†	17.2†
5	497	605	109	19	23	7.8†	13.2†
6	498	607	108	17	22	11.1†	16.1†
7	604	713‡	110‡	13	15	5.0	12.4†
8	604	700	96	14	16	4.6	16.3†
9	604	696	92	14	18	3.1	17.5†
10	606	701	95	15	15	3.9	23.6†
11	603	700	97	13	16	3.4	17.2†
12	604	698	94	14	18	4.5	13.2†
13	702	813†	111	16	15	14.1†	13.8†
14	702	812†	109	12	14	15.2†	16.5†
15	702	814†	111	18	14	11.4†	12.0†
16	703	812†	109	12	15	10.4†	10.0†
17	702	814†	111	15	15	10.8†	12.5†
18	703	813†	110	18	15	14.1†	12.7†
19	808	991	183	23	139*	44.1†	64.7†
20	808	974	166	23	146*	61.1†	71.0†
21	808	1004	196	23	126*	37.8†	59.3†
22	808	992	185	24	133*	47.4†	67.2†
23	807	976	169	24	144*	60.8†	69.5†
24	807	1000	193	24	120*	43.8†	63.0†

* No filter specification.
† Fails to meet filter specification.
‡ Rejectable as outlier: $\alpha = 0.01$.

spectral response itself, and (3) the reproducibility of the digitization of the RSR curves. Note that the June 1980 PF RSR curves were more difficult to digitize than the June 1981 curves.

Table C-2 lists the differences in the means and standard deviations of the PF RSR characteristics. Several explanations are suggested for the large band 4 mean upper-band edge (and flatness) differences that were measured: (1) a drift in the response of the reference photodiode used in measuring RSR, (2) poorer monochrometer-to-collimator alignment for the earlier tests, or (3) instrument operating temperature differences between the tests (Yuh, private communication).

TABLE C-2. DIFFERENCES IN PROTOFLIGHT RELATIVE SPECTRAL RESPONSES BETWEEN JUNE 1980 AND JUNE 1981 MEASUREMENTS

	Band Edge (nm)			Slope Interval (nm)		Spectral Flatness (%)	
Band	Lower	Upper	Width (nm)	Lower	Upper	Positive	Negative
			Means				
1	−2.0	−1.7	+0.2	−2.5	+1.1	−4.2	−6.0
2	−1.2	−3.2	−2.0	−1.3	0.0	+2.9	−3.9
3	−1.6	0.0	+1.6	0.0	0.0	+0.6	−0.1
4	0.0	+33.0	+33.0	−0.3	−24.5	−19.4	−12.2
			Standard Deviations				
1	−0.02	+0.40	+0.03	−0.67	+0.24	−0.4	+1.1
2	−0.34	−1.30	−1.36	−0.36	+0.45	+0.7	−1.5
3	+0.37	−0.03	+0.17	−1.77	+0.10	+0.9	+0.8
4	−0.17	+2.70	+2.30	−0.45	−1.10	−2.4	+2.5

The RSR parameters were categorized on the basis of their expected reproducibility, and a threshold difference for each category was established for use in comparing multispectral scanners. All the band edges (except for band 4 upper edge), widths (except for band 4), and slope intervals (except for band 4 upper slope) are primarily filter-determined and were deemed of similar reproducibility. Thresholds of 3-nm for means and 1.8 nm for standard deviations (the maximum observed differences as shown in Table B-2) were established. The other categories that were established are

- The principally detector-determined characteristics of band 4 upper-band edge, width, and upper-slope interval with thresholds of 33 nm for means and 2.7 nm for standard deviations;
- The positive spectral flatness for bands 1 through 3 with thresholds of 4 percent for means and 0.9 percent for standard deviations;
- The negative spectral flatness for bands 1 through 3 with thresholds of 6 and 1.5 percent;
- The positive spectral flatness for band 4, 19 and 2.4 percent; and
- The negative spectral flatness for band 4, 12 and 2.5 percent

Simulated outputs for soil and soybean targets were also generated by using the June 1980 data, and differences were computed between these outputs and the simulated outputs by using the June 1981 RSR data (Table C-3).

TABLE C-3. DIFFERENCES IN SIMULATED MSS OUTPUTS USING JUNE 1980 VERSUS JUNE 1981 RELATIVE SPECTRAL RESPONSE DATA

Target	Band 1	Band 2	Band 3	Band 4
		Means		
Soy	+0.16	+0.04	−0.89	−1.15
Soil	−0.02	+0.07	−0.04	−0.36
	Maximum Differences Between Channels			
Soy	−0.02	−0.29	+1.09	+0.30
Soil	−0.01	−0.01	+0.03	+0.10

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MARS' geologists have interpreted imagery associated with projects that located water in the Nigerian desert, oil-bearing reefs in Texas, hydrocarbon-bearing structures in Guatemala, Indonesia, Mexico, Cameroon, Equitorial Guinea, Gabon, Taiwan, and the U.S.A., and identified geothermal energy sources in Japan, Philippines, Taiwan and the U.S.A. They have also performed surveys and fracture analyses for major dams, pipelines, and nuclear power plants.

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Appendix D
Protoflight and Flight Model Digitized Relative Spectral Responses

Table D-1. Protoflight Digitized Relative Spectral Responses (June 1981)

Band 1

Wavelength (nanometres)	Channel 1	2	3	4	5	6
450	0.	0.	0.	0.	0.	0.
460	0.	0.	0.	0.	0.	0.
470	1.	1.	1.	1.	1.	1.
480	3.	3.	3.	4.	4.	4.
490	23.	24.	24.	27.	28.	26.
500	68.	68.	68.	73.	74.	71.
510	87.	88.	89.	90.	93.	89.
520	93.	95.	93.	95.	94.	93.
530	98.	98.	100.	100.	100.	100.
540	98.	98.	96.	97.	99.	97.
550	100.	100.	98.	98.	98.	98.
560	97.	97.	95.	94.	95.	96.
570	96.	98.	95.	92.	92.	96.
580	89.	91.	86.	84.	82.	88.
590	90.	91.	88.	85.	85.	90.
600	68.	66.	65.	60.	58.	67.
610	38.	35.	37.	34.	32.	38.
620	9.	8.	9.	8.	8.	9.
630	4.	4.	4.	4.	4.	4.
640	2.	2.	2.	2.	2.	2.
650	1.	1.	1.	1.	1.	1.

Band 2

Wavelength (nanometres)	Channel 7	8	9	10	11	12
550	0.	0.	0.	0.	0.	0.
560	0.	0.	0.	0.	0.	0.
570	0.	0.	0.	0.	0.	0.
580	0.	0.	0.	0.	0.	0.
590	3.	3.	2.	3.	2.	4.
600	39.	41.	35.	38.	36.	42.
610	82.	84.	79.	80.	74.	82.
620	97.	97.	94.	94.	95.	95.
630	98.	99.	100.	100.	100.	99.
640	100.	100.	100.	99.	99.	100.
650	97.	96.	95.	95.	96.	94.
660	89.	92.	93.	89.	97.	91.
670	88.	90.	91.	90.	95.	88.
680	81.	86.	86.	85.	91.	82.
690	72.	80.	81.	80.	88.	76.
700	70.	30.	28.	34.	37.	28.
710	44.	6.	5.	7.	8.	5.
720	12.	2.	2.	2.	1.	1.
730	2.	1.	1.	1.	0.	0.
740	0.	0.	0.	0.	0.	0.
750	0.	0.	0.	0.	0.	0.

Band 3

Wavelength (nanometres)	Channel 13	14	15	16	17	18
650	0.	0.	0.	0.	0.	0.
660	0.	0.	0.	0.	0.	0.
670	0.	0.	0.	0.	0.	0.
680	1.	1.	1.	1.	1.	1.
690	10.	8.	9.	7.	8.	8.
700	50.	44.	46.	40.	47.	46.
710	92.	93.	90.	88.	92.	92.
720	100.	100.	100.	100.	100.	100.
730	95.	94.	91.	95.	94.	92.
740	89.	90.	88.	91.	88.	86.
750	89.	89.	89.	92.	90.	85.
760	85.	86.	88.	90.	86.	81.
770	82.	81.	83.	87.	83.	75.
780	77.	79.	83.	85.	80.	73.
790	74.	72.	79.	79.	74.	70.
800	66.	67.	73.	74.	69.	63.
810	67.	58.	72.	69.	66.	58.
820	13.	10.	15.	14.	16.	13.
830	2.	2.	3.	2.	2.	2.
840	0.	1.	1.	1.	1.	0.
850	0.	0.	1.	0.	0.	0.

Band 4

Wavelength (nanometres)	Channel 19	20	21	22	23	24
740	0.	0.	0.	0.	0.	0.
760	0.	0.	0.	0.	0.	0.
780	1.	1.	1.	1.	1.	1.
800	18.	20.	18.	21.	21.	21.
820	98.	100.	94.	100.	100.	100.
840	100.	99.	95.	99.	97.	99.
860	98.	96.	97.	97.	96.	98.
880	95.	94.	94.	93.	93.	97.
900	94.	93.	96.	92.	93.	97.
920	97.	91.	100.	95.	90.	95.
940	90.	84.	96.	85.	84.	90.
960	84.	73.	88.	80.	78.	81.
980	80.	66.	82.	67.	75.	72.
1000	66.	54.	73.	56.	63.	60.
1020	51.	41.	63.	46.	52.	49.
1040	47.	34.	56.	36.	44.	41.
1060	39.	25.	43.	28.	36.	31.
1080	30.	20.	35.	23.	29.	26.
1100	21.	14.	25.	16.	19.	18.
1120*	11.	7.	15.	9.	10.	9.
1140*	3.	1.	6.	0.	2.	1.

* Extrapolated.

TABLE D-2. FLIGHT DIGITIZED RELATIVE SPECTRAL RESPONSES

Band 1

Wavelength (nanometres)	Channel 1	2	3	4	5	6
450	0.	0.	0.	0.	0.	0.
460	0.	0.	0.	0.	0.	0.
470	0.	0.	1.	1.	1.	1.
480	2.	2.	3.	3.	3.	3.
490	21.	20.	23.	24.	21.	22.
500	63.	58.	67.	71.	63.	64.
510	81.	75.	86.	88.	81.	82.
520	87.	82.	91.	94.	88.	88.
530	96.	92.	98.	100.	96.	96.
540	95.	93.	96.	97.	96.	95.
550	100.	99.	100.	100.	100.	100.
560	98.	98.	95.	96.	98.	98.
570	100.	100.	96.	94.	98.	98.
580	95.	96.	89.	87.	93.	95.
590	99.	98.	92.	88.	94.	97.
600	76.	76.	68.	67.	75.	76.
610	40.	40.	36.	36.	39.	40.
620	9.	8.	8.	9.	9.	9.
630	4.	4.	3.	3.	4.	3.
640	2.	2.	1.	1.	2.	1.
650	1.	1.	0.	0.	1.	0.

Band 2

Wavelength (nanometres)	Channel 7	8	9	10	11	12
550	0.	0.	0.	0.	0.	0.
560	0.	0.	0.	0.	0.	0.
570	0.	0.	0.	0.	0.	0.
580	0.	0.	0.	0.	0.	0.
590	3.	3.	3.	3.	3.	3.
600	36.	37.	38.	40.	38.	39.
610	77.	76.	81.	84.	79.	79.
620	92.	92.	94.	96.	94.	93.
630	97.	98.	99.	99.	98.	97.
640	100.	100.	100.	100.	100.	100.
650	96.	96.	94.	95.	95.	96.
660	93.	93.	89.	89.	92.	93.
670	91.	90.	86.	85.	90.	92.
680	88.	86.	82.	80.	88.	89.
690	84.	81.	77.	74.	83.	85.
700	37.	31.	34.	31.	34.	37.
710	7.	6.	6.	5.	6.	6.
720	2.	1.	1.	1.	1.	1.
730	0.	0.	0.	0.	0.	0.
740	0.	0.	0.	0.	0.	0.
750	0.	0.	0.	0.	0.	0.

Band 3

Wavelength (nanometres)	Channel 13	14	15	16	17	18
650	0.	0.	0.	0.	0.	0.
660	0.	0.	0.	0.	0.	0.
670	0.	0.	0.	0.	0.	0.
680	1.	1.	1.	1.	1.	1.
690	6.	7.	7.	5.	6.	7.
700	25.	28.	27.	23.	26.	27.
710	85.	88.	91.	85.	88.	88.
720	100.	100.	100.	100.	100.	100.
730	95.	93.	95.	92.	94.	94.
740	88.	89.	90.	89.	85.	90.
750	88.	90.	89.	87.	88.	89.
760	90.	88.	89.	85.	87.	89.
770	84.	84.	82.	79.	83.	84.
780	83.	82.	83.	81.	81.	81.
790	81.	78.	79.	78.	78.	79.
800	76.	73.	72.	71.	71.	72.
810	75.	71.	70.	71.	71.	73.
820	17.	19.	16.	18.	19.	20.
830	2.	2.	2.	2.	2.	3.
840	1.	0.	0.	1.	0.	1.
850	0.	0.	0.	0.	0.	0.

Band 4

Wavelength (nanometres)	Channel 19	20	21	22	23	24
740	0.	0.	0.	0.	0.	0.
760	0.	0.	0.	0.	0.	0.
780	1.	1.	1.	1.	1.	1.
800	15.	15.	15.	14.	15.	13.
820	95.	93.	92.	94.	95.	95.
840	100.	96.	98.	100.	100.	100.
860	99.	97.	96.	98.	96.	99.
880	97.	98.	97.	98.	98.	98.
900	98.	98.	99.	95.	97.	99.
920	95.	100.	100.	93.	96.	97.
940	91.	94.	95.	84.	91.	94.
960	85.	91.	93.	77.	82.	87.
980	78.	87.	86.	68.	76.	81.
1000	70.	77.	78.	58.	68.	71.
1020	54.	62.	65.	47.	55.	57.
1040	46.	55.	54.	37.	48.	50.
1060	37.	42.	43.	30.	36.	37.
1080	27.	33.	34.	23.	29.	30.
1100	18.	24.	23.	16.	20.	21.
1120*	10.	14.	14.	9.	11.	12.
1140*	3.	5.	5.	3.	4.	4.

* Extrapolated.