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The Time-Space Relationships of the Data Points (Pixels) of the Thematic Mapper and Multispectral Scanner or "The Myth of Simultaneity"

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All measurement values are expressed in the International System of Units (SI) in accordance with NASA Policy Directive 2220.4, paragraph 4.

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INTRODUCTION

When speaking to users of satellite scanner data, it is always interesting to find how widespread is the notion which equates the temporal nature of that scanner data with the unit time aspect of photographic data. I call this the "myth of simultaneity." For most applications, equating the two may make little difference, but I believe it important that the user at least be aware of it. In this paper, the examples of the multispectral scanner (MSS) on Landsats 1, 2, and 3 and the Thematic Mapper (TM) of Landsat D will be used to describe the concept and degree of non-simultaneity of scanning system data. For overall Landsat systems operation and performance refer to the references. This article will address itself primarily to the time-space aspects of scanner data acquisition and to those parts of the MSS and TM systems that are related to this phenomena.

Let us briefly address the time aspect of "photographic" systems. In systems of this type, all data in the scene are acquired at the same point in time. It does not matter if the recording medium is film, the light sensitive surface of a vidicon tube, or any other photosensitive recording medium. The latter may be subsequently scanned for telemetry and/or processing purposes, but this has no essential bearing on the time relationship among data points within the scene. Every part of the scene contains data that were frozen at a time zero, the time the scene was acquired. Landsats 1 and 2 had three Return Beam Vidicon (RBV) cameras, each spectrally filtered for a different waveband, but all focused on the same area and shuttered simultaneously every 25 seconds. The vidicons were subsequently scanned sequentially, but the data acquired on each were for that same time of exposure.

Landsat 3 uses a panchromatic two-camera system. The cameras are not exposed simultaneously, but the data acquired by either camera for a given scene are still all at a unique time. While in each case the data are scanned and telemetered at a period subsequent to exposure, every datum within a given scene still has the property of time-simultaneity.

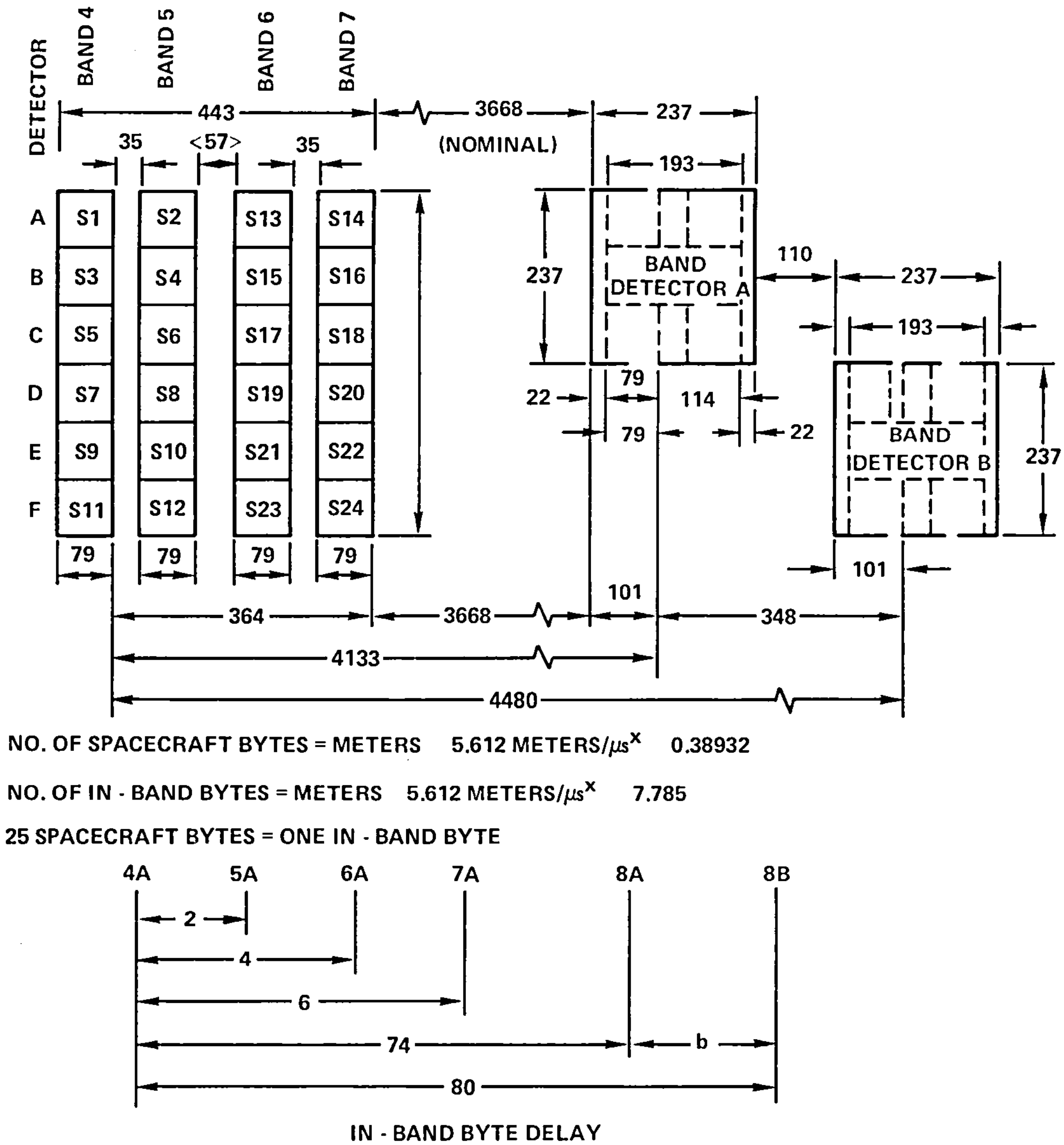
LANDSATS 1, 2, and 3

This brings us to the "myth of simultaneity" with regard to scanner data. Many users of Landsat MSS data have the intuitive feeling that the data they are working with have the same time quality as described above. In most cases this will make little difference in data-use, providing the mechanics of scanning are known and the data processing system is adequate. However, the point of interest here is that in most scanner systems no datum that goes into making up a scene or image is acquired simultaneously with any other datum in that scene.* However, the time differences may be, and usually are, minute. In the case of the MSS of Landsats 1, 2, and 3 these times may be as small as a fraction of a microsecond, but the time differences are finite and cumulative. The last datum in a Landsat scene will be taken close to 29 seconds after the first. Thus each of the 31 million or so pixels that go into making a 4 spectral band scene has been taken at a different time. Figure 1 is the layout of the optical fiber ends of the reflective bands and the ports of the thermal band relay optics in the focal plane of the Landsat MSS. The static equivalent ground dimensions are shown across and between the optical elements, as well as the equivalent number of spacecraft and in-band bytes. An in-band byte is equivalent in time to that necessary to measure one minor frame (MNFR); a minor frame is a single sampling of each of the 24 + 1 elements that comprise the optical matrix in the focal plane (1 MNFR = 9.958 microseconds). A spacecraft byte equates to the time necessary to take the measurement of any given optical element (0.39832 microseconds). These measurements are subsequently amplified, digitized, etc. Descriptions of these operations can be found in the references, but are not needed to understand arguments presented here. Figure 2 is the time-distance layout of one 4-band line of the MSS optical matrix. The bottom line represents a series of pixel-equivalent areas along the line of scan of the MSS mirror.** Keep in mind that we are using an idealized situation, where systematic perturbations such as spacecraft attitude and linearity of mirror sweep have been corrected, and where altitude is constant. Two directions of motion are involved relative to the focal plane matrix: the movement of the spacecraft roughly in the direction of the six lines per band and the motion of the scan of the mirror across the bands. For Figure 2 we take into consideration only the scan motion. At time T_o we read the output of sensor S1, the start of our minor frame measurement, in the sequence indicated in Figure 1.

If we allow 0.39832 microseconds between individual measurements (one spacecraft byte), S2 will be measured at T + 0.39832 microseconds. The cross scan velocity is calculated to be 5.612 meters per microsecond. The static equivalent ground distance (a non-moving mirror looking at a non-moving Earth) between centers of S1 and S2 is (79÷2) + (79÷2) + 35 = 114 (based upon a nominal altitude of about 918 km).† However, in the 0.39832 microseconds between measurement S2 has moved about 2 meters (0.39832 microseconds x 5.612 meters per microsecond). Thus, the actual center distance between the two viewed areas is 112 meters, which is equivalent to 2 pixels in the line of scan. So, when the measurement is made by detector S2, it is actually viewing a piece of ground that is 112 meters west of the ground that had been measured 0.39832 microseconds before by S1. This would be pixel P-2 in Figure 2.

In Figure 1, band 6 on that line is not sampled until 12 time-measurement units (spacecraft bytes) later. The distance that the scan has moved in this time interval is 12 x 0.39 x 5.6 $\simeq$ 26 meters. The static space distance between these 2 pixels is 79 + 35 + 79 + 57 = 250 meters. However, because the scan has moved 26 meters eastward during the time between the measurement on S1 (band 4) and S13 (band 6), the sensor instantaneous field of view (IFOV) is looking at a piece of ground

*There is one aspect of the thematic mapper that is an exception to this generalization. This will be described later.
**See Appendix A
†Actual Landsat altitudes vary from 880 km 940 km, so that linear IFOV may vary from 76 m to 81 m.



DETECTOR
BAND 4
BAND 5
BAND 6
BAND 7
443
3668
(NOMINAL)
237
35
<57>
35
193
A
B
C
D
E
F
S1
S2
S13
S14
S3
S4
S15
S16
S5
S6
S17
S18
S7
S8
S19
S20
S9
S10
S21
S22
S11
S12
S23
S24
79
79
79
79
BAND
DETECTOR A
110
237
193
79
22
114
79
22
BAND
DETECTOR B
237
101
101
364
3668
348
4133
4480
NO. OF SPACECRAFT BYTES = METERS 5.612 METERS/μs X 0.38932
NO. OF IN - BAND BYTES = METERS 5.612 METERS/μs X 7.785
25 SPACECRAFT BYTES = ONE IN - BAND BYTE
4A
5A
6A
7A
8A
8B
2
4
6
74
b
80
IN - BAND BYTE DELAY

Figure 1.

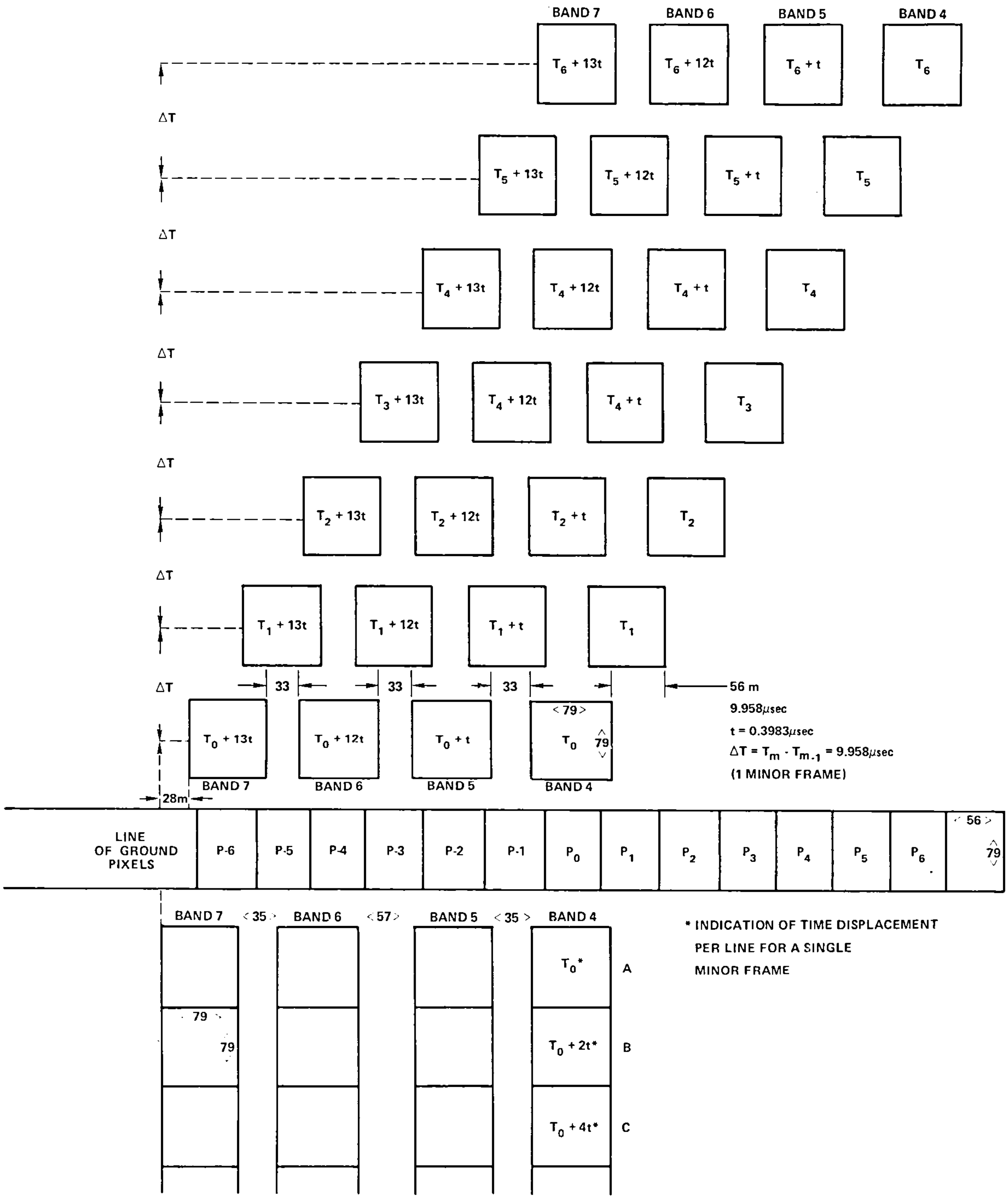

BAND 7
BAND 6
BAND 5
BAND 4
T6 + 13t
T6 + 12t
T6 + t
T6
ΔT
T5 + 13t
T5 + 12t
T5 + t
T5
T4 + 13t
T4 + 12t
T4 + t
T4
T3 + 13t
T4 + 12t
T4 + t
T3
T2 + 13t
T2 + 12t
T2 + t
T2
T1 + 13t
T1 + 12t
T1 + t
T1
33
56 m
9.958μsec
t = 0.3983μsec
ΔT = Tm - Tm-1 = 9.958μsec
(1 MINOR FRAME)
79
T0 + 13t
T0 + 12t
T0 + t
T0
28m
LINE OF GROUND PIXELS
P-6
P-5
P-4
P-3
P-2
P-1
P0
P1
P2
P3
P4
P5
P6
56
35
57
T0*
T0 + 2t*
T0 + 4t*
A
B
C
* INDICATION OF TIME DISPLACEMENT PER LINE FOR A SINGLE MINOR FRAME

Figure 2.

224 meters (250–26) to the west of that viewed by S1 within that same minor frame, or the equivalent of 4 pixels. On Figure 2 this would be pixel P-4. The detector that views band 7 on that line (S14) is measured one spacecraft byte later. Its space-time relationship to S13 is exactly the same as S2 was to S1, so it is 2 pixels to the west of S13, or 6 pixels (336 meters) to the west of P-0. Thus the measurement made by the four detectors in a single line during a single minor frame (in-band byte) were at four different locations (P-0, P-2, P-4, P-6).

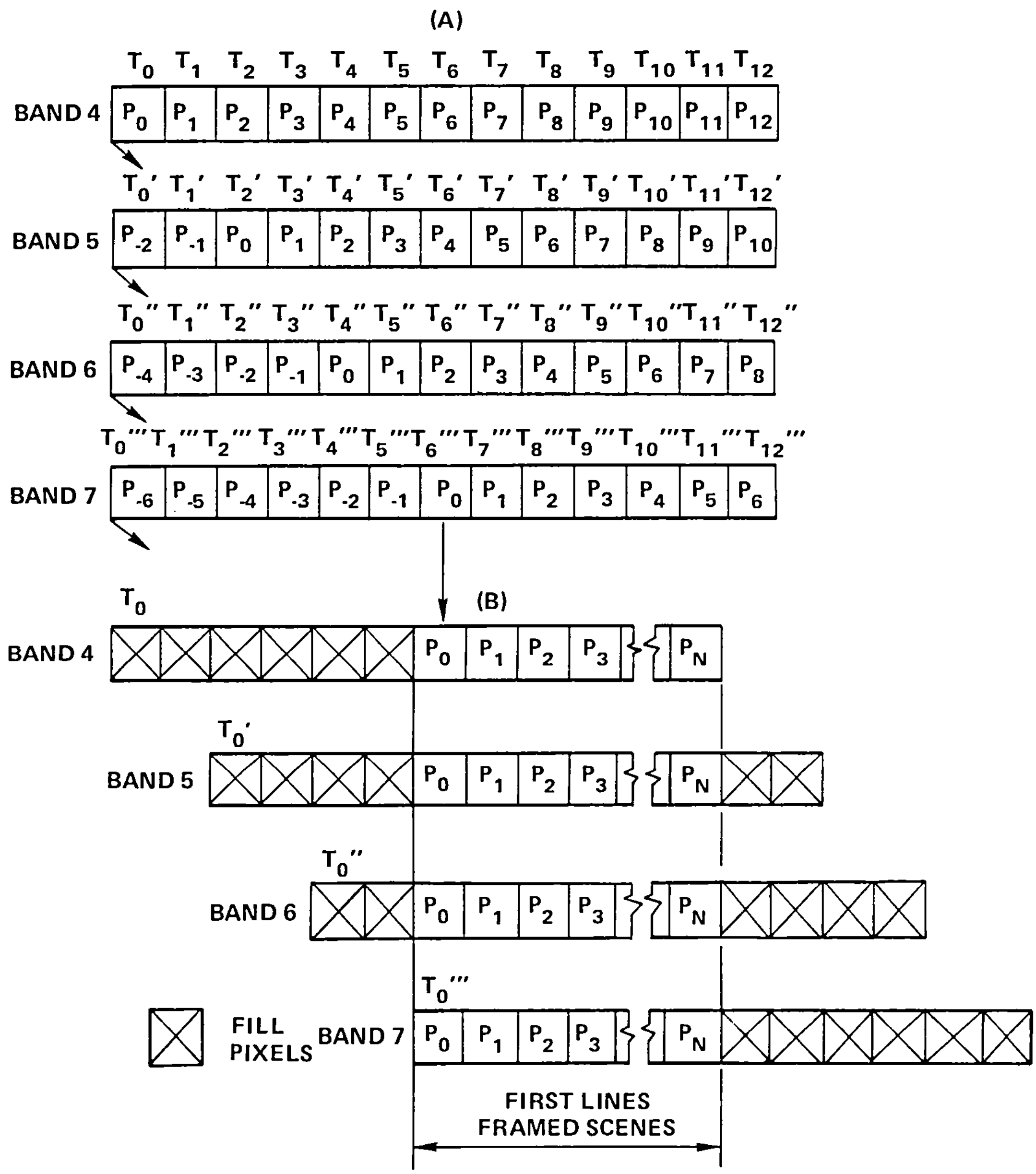
Within each band, for a given detector line, the pixels will be contiguous, moving eastward. However, if they were indexed by time, i.e., minor-frame by minor-frame (Tn), problems in spatial matching would arise. In the case of single-band black and white photoprints that were to be used to make color images you would have a 2 pixel difference between sequential bands. In order to correct this in digital tapes, pixels are added in front of each line of each band. In this way, the result is spatial alignment for the imagery, and the proper corrections made, computer compatible tapes (CCTs) are created (see Figure 3). The per-line algorithm for the number of pixels to be added in front of the band is N=8 - (2xn); where N-number of pixels to be inserted in front, n=number of the MSS band; n=1 is the green band, etc. Actually, six pixels are added to each line in A- and X-format CCTs (so-called "raw" tapes), so that if 2 are added in front, the 4 would be added at the end.

So far, only the single-line time relationships have been discussed, and it has been assumed that within a line the motion due to the rotation of the Earth is insignificant. We will continue to treat the latter point, as such, within a single sweep because during the 33 milliseconds required the 185 km scan, the Earth has rotated only about 153 meters at the equator and (153 x cosine latitude) 153 x .766 = 117 meters at 40 degrees latitude. This amounts to about 3 cm per pixel.

In the line-to-line relationships, the simultaneity problem must again be addressed. Figure 1 shows that as we sample from line-to-line with a single band, there is a two measurement-time difference which is equal to 4.47 meters. There are 10 measurement times between line 1 and line 6 in any given band for a given minor frame, 22.4 meters or about 28 percent displacement. When the X-format CCTs and A-format CCTs (so-called raw data tapes) are made, this is ignored. However, when individual photo images are made (via the electron beam recorder or the laser beam recorder) this correction factor is included. Geometerically-corrected digital tapes (P-tapes) take this into consideration in the resampling process.

It was stated above that relative movement of the target due to the Earth's rotation could be ignored for a single sweep, but for the total scene (2,350 lines) this translational factor becomes significant. In the 185 km length of an MSS image, the time of travel along the orbital path is 28.6 seconds. In that time, the Earth has rotated a distance in kilometers equal to 0.4638 x cos latitude x 28.6, at a given line of latitude. At 40° north, this would be a 10.2 km displacement westward of the last line over the first.

This is usually corrected in the image display systems by inserting pixels that effectively move lines westward. This is not a resampling operation. It only inserts an appropriate integral number of dummy pixels at the beginning and end of each line in conformance with some algorithm that ensures that the integrity of each 6-line sweep is maintained. The result of such an algorithm is shown in Table 1. Input routines that make this correction usually remove the synthetic pixels, that



(A)
BAND 4
BAND 5
BAND 6
BAND 7
(B)
BAND 4
BAND 5
BAND 6
BAND 7
FILL PIXELS
FIRST LINES FRAMED SCENES

Figure 3.

Table 1.

LINE NUMBER	PIXELS INSERTED
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	1
20	1
21	1
22	1
23	1
24	1
25	1
26	1
27	1
28	1
29	1
30	1
31	2
32	2
33	2
34	2
35	2
36	2
37	2
38	2
39	2
40	2
41	2
42	2
43	3
44	3
480	34
481	35
482	35
483	35
484	35
485	35
486	35
487	35
488	35
489	35
490	35
491	35
492	35
493	36
494	36
495	36
496	36
497	36
498	36
499	36
500	36
501	36
502	36
503	36
504	36
505	36
506	36
507	36
508	36
509	36
510	36
511	37
995	72
996	72
997	73
998	73
999	73
1000	73
1001	73
1002	73
1003	73
1004	73
1005	73
1006	73
1007	73
1008	73
1009	73
1010	73
1011	73
1012	73
1013	73
1014	73
1015	74
1016	74
2308	168
2309	168
2310	168
2311	169
2312	169
2313	169
2314	169
2315	169
2316	169
2317	169
2318	169
2319	169
2320	169
2321	169
2322	169
2323	170
2324	170

had been inserted in the CCTs during production to ensure equal line length, prior to insertion of skew corrective pixels.

With the description of the fact of non-simultaneity we have assumed fairly ideal conditions and minimized perturbations such as nonlinearities in the mirror sweep and other factors that cause deviations from the desired space-time relationships. The main point to keep in mind relative to the MSS is that each pixel value is a separate, but time-space related measurement that must be reassembled to create a geographic scene. In the following section on the TM we will observe that these time-space relationships are even more protracted and their acquisition and reassemblement is even more complicated.

LANDSAT-D THEMATIC MAPPER

The thematic mapper (TM) performance represents changes from the Multispectral Scanner (MSS) that are different in both quality and quantity, and thus the time-space relationships are more complex. The number of bands (7) and the number of lines per band (16), plus auxiliary words, make a TM minor frame count of 102 (versus 25 for the MSS). But the most significant factors contributing to the added complexity in time-space relationship of pixels are that the sweep of the TM is active in both directions, and resulting in the timing and reading operations of the multiplexer which are quite different. These operational factors grew out of system performance requirements to provide sufficient dwell time to get an acceptable signal-to-noise ratio for each pixel measurement. The major optical performance difference is that the need to have the active sweep in both directions, precludes the use of the simple planar motion of the Scan Mirror across the path of flight to achieve the full raster effect that this achieves in the case of the MSS. You will recall in the MSS, using the scan mirror motion alone, plus active sweep in one direction only, allows each set of six lines in a sweep to be abutted to its immediate predecessor (see Figure 4). However, if we use this motion alone to collect data in both directions we get a situation such as shown in Figure 5a, in which part of the sweep covers the same area twice (overlap) and part will miss areas altogether (underlap). A solution to this is shown in Figure 5b. Here the direction of sweep is perpendicular to the line of flight and each half-cycle. However, if this is to be achieved the sweep motion must have two things that cannot be achieved by a scan-mirror motion alone. First, the vector of the sweep ground trace must be displaced linearly opposite to the direction of flight during the sweep. Secondly, at the end of each half-sweep it must be displaced the equivalent distance of the cross-sweep width, in the direction of flight. The vector diagram is as shown in Figure 5c. This is achieved by means of a Scan Line Corrector (SLC). (See Appendix B for a description of the optical path relationships of the Scan Mirror and the SLC).

At this point let us introduce the TM focal plane layout of the optical detectors for the 7 bands. It is an "effective" focal plane, because there are actually two physical locations for the two parts of the detector system: first, the primary focal plane, which contains the uncooled silicon detectors for the first 4 reflective bands (1) 0.45–0.52 micrometer (blue) and (2) (0.52–0.60 micrometers and 2.08–2.35 micrometers) require cooled (95 k) indium antimonide detectors. These are located physically behind the primary focal plane, and along with the Mercury-Cadmium-Telluride (Hg CdTe) thermal IR detectors are on a separate refrigerated mount. These detectors are made to optically appear in the primary focal plane by means of relay optics. In Figures 6 and 7 note the relatively

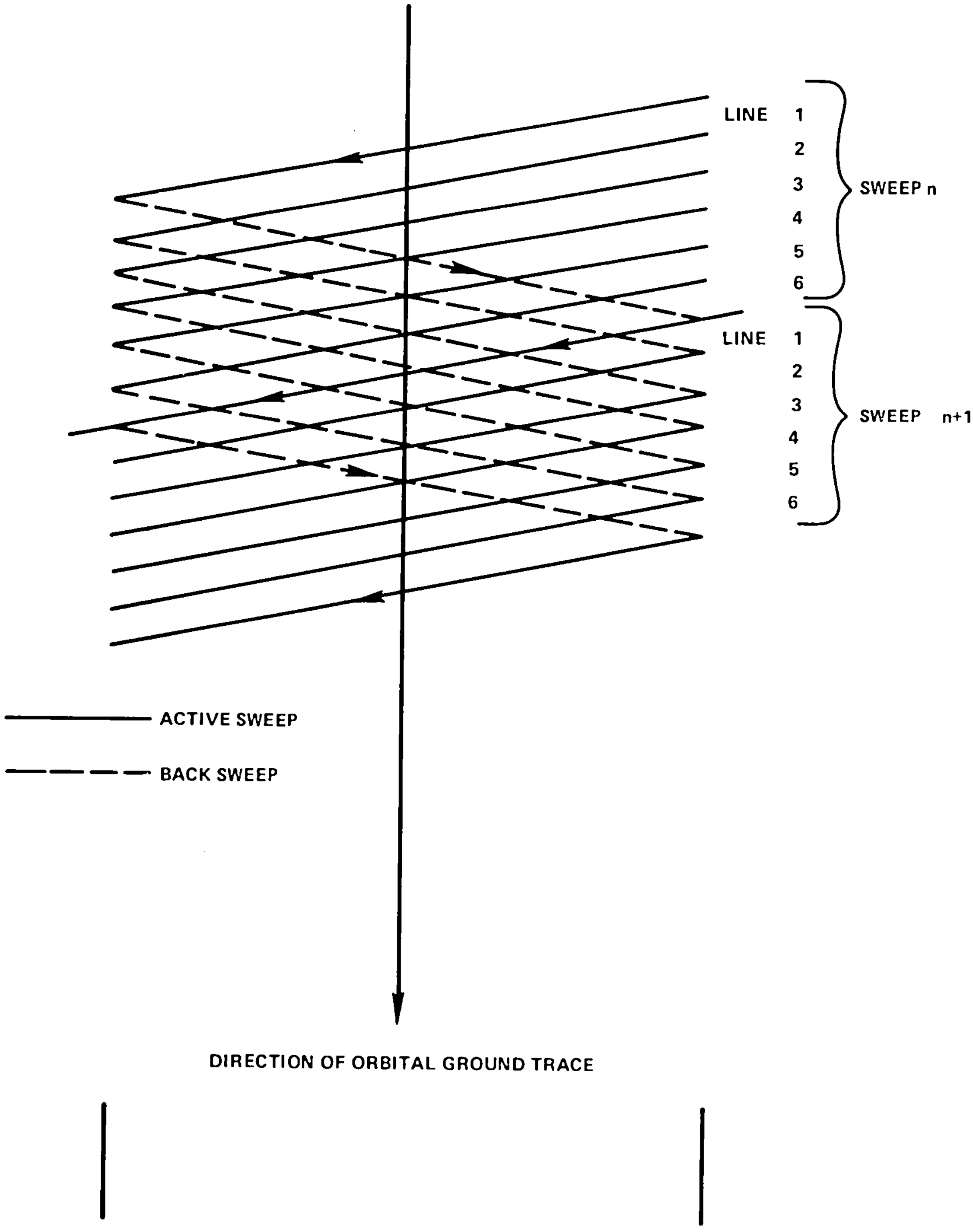

LINE 1
2
3
4
5
6
SWEEP n
LINE 1
2
3
4
5
6
SWEEP n+1
ACTIVE SWEEP
BACK SWEEP
DIRECTION OF ORBITAL GROUND TRACE

Figure 4.

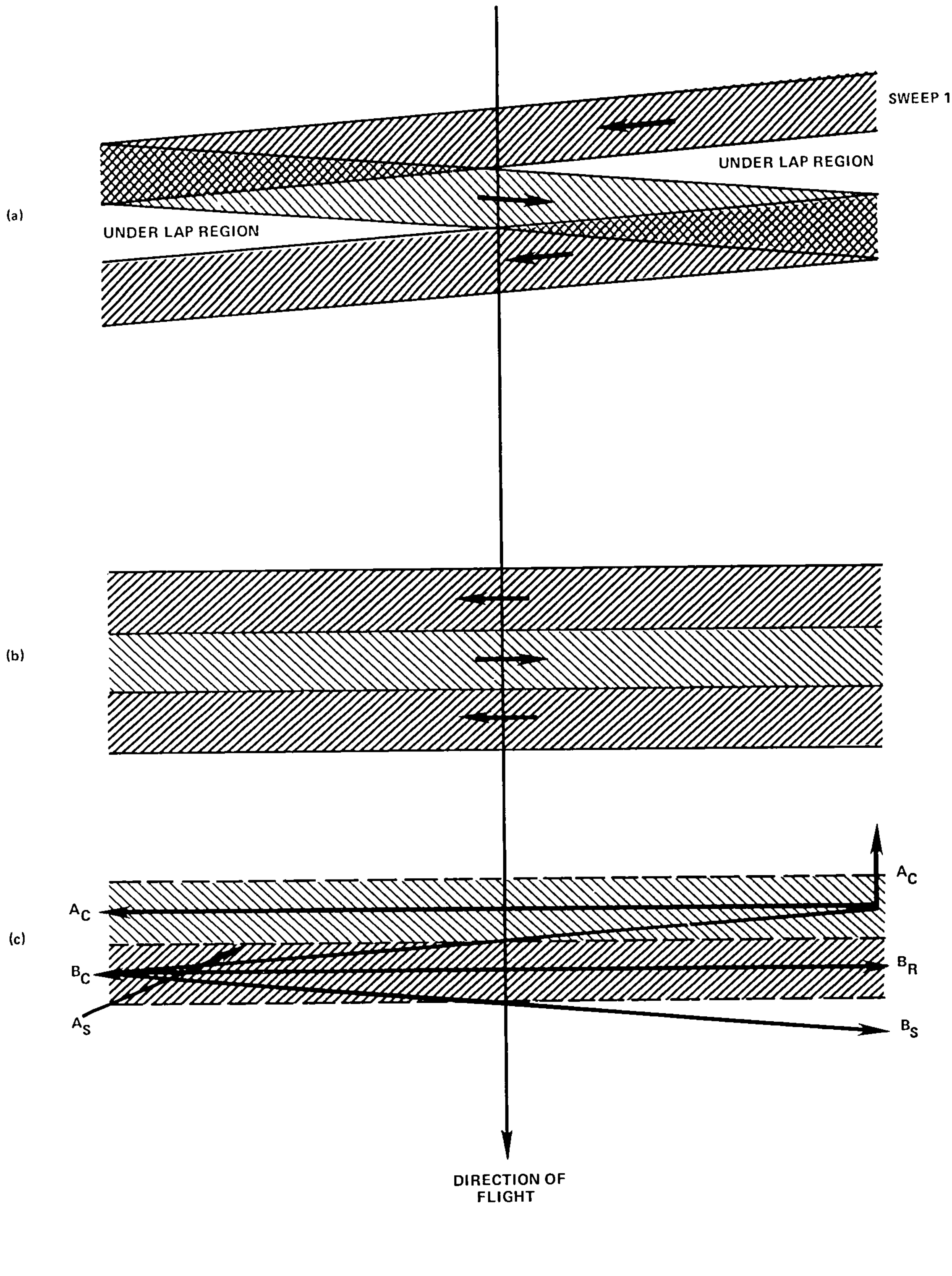

SWEEP 1
UNDER LAP REGION
(a)
UNDER LAP REGION
(b)
A_C
A_C
(c)
B_C
B_R
A_S
B_S
DIRECTION OF
FLIGHT

Figure 5.

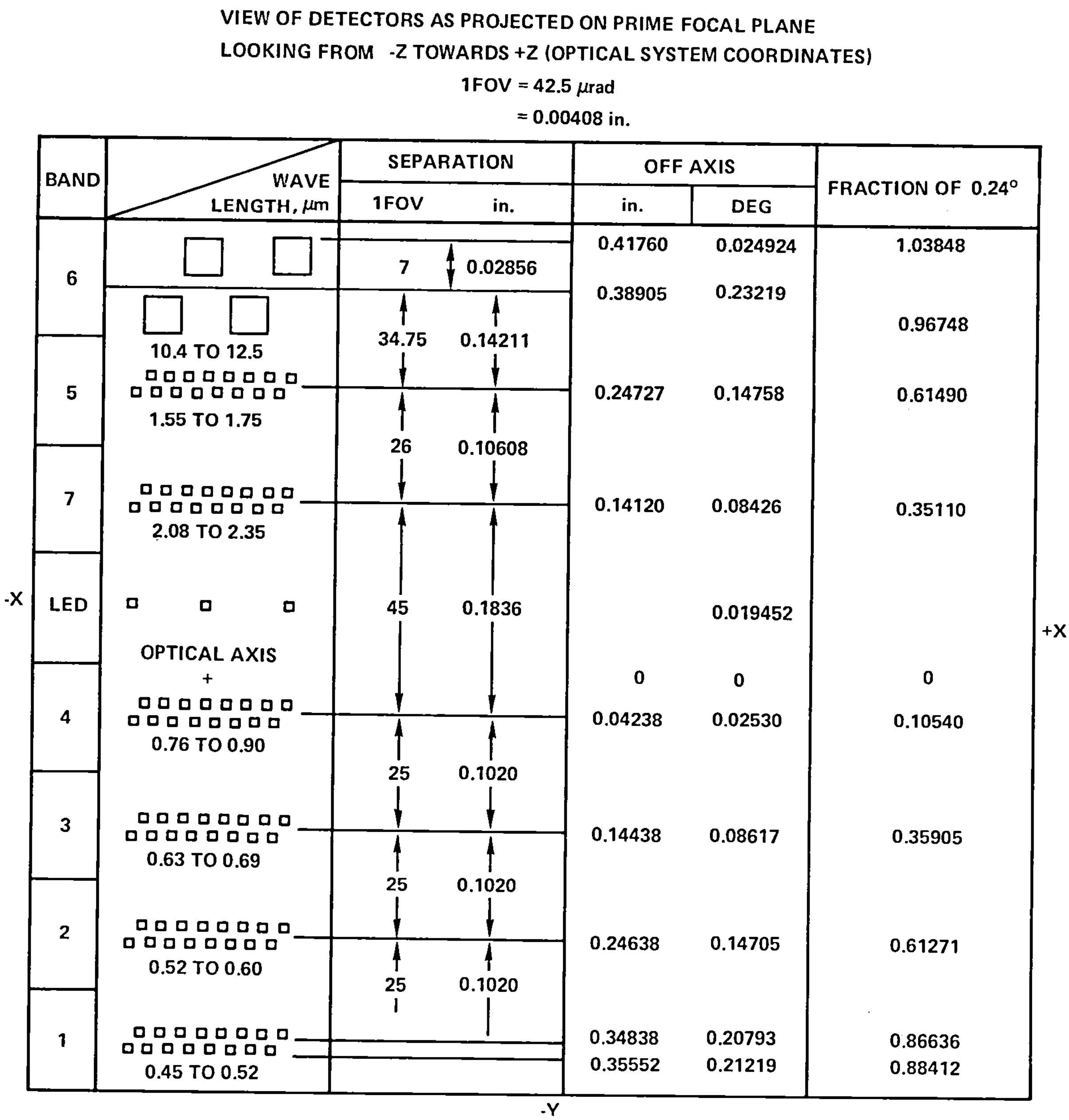


Figure 6. Detector Projection at Prime Focal Plane.

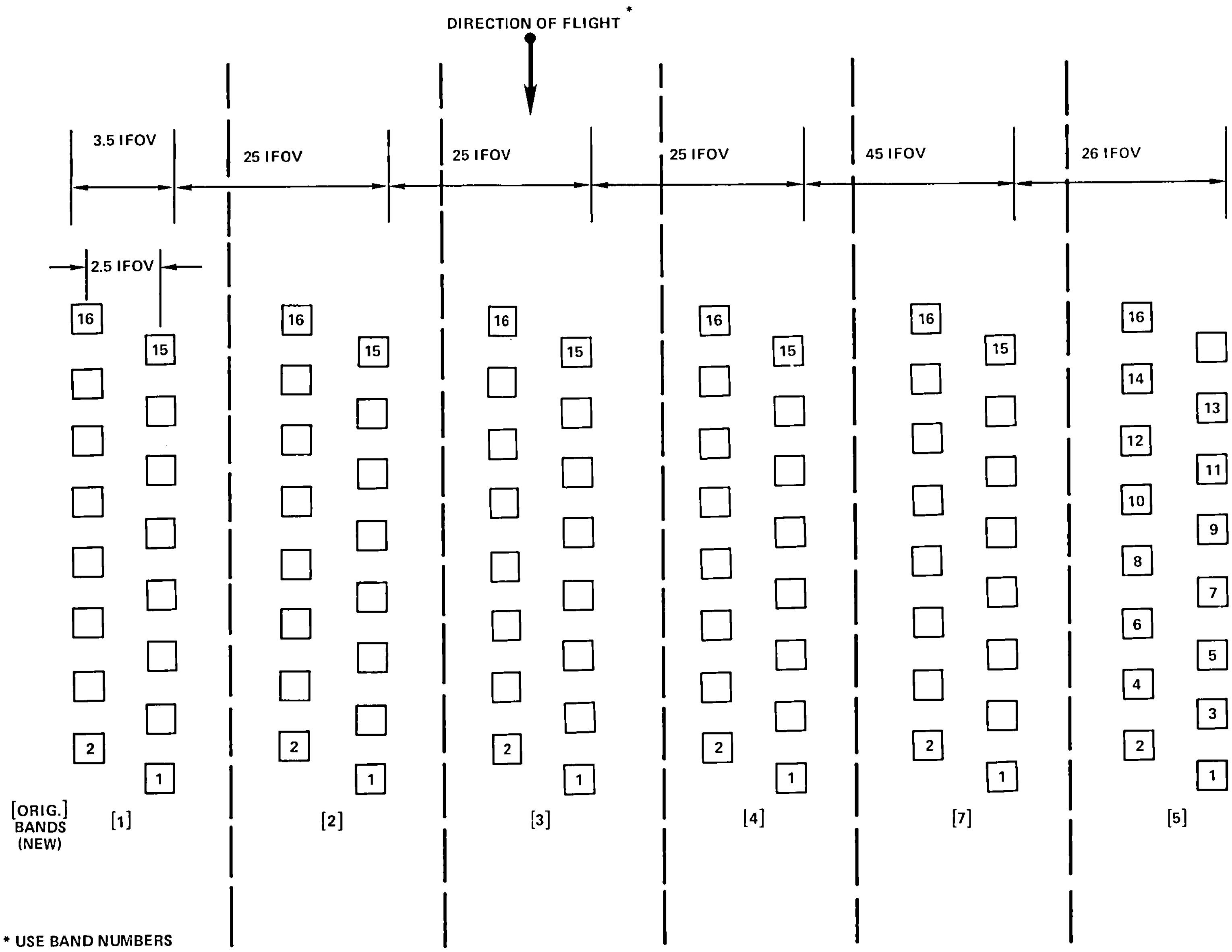
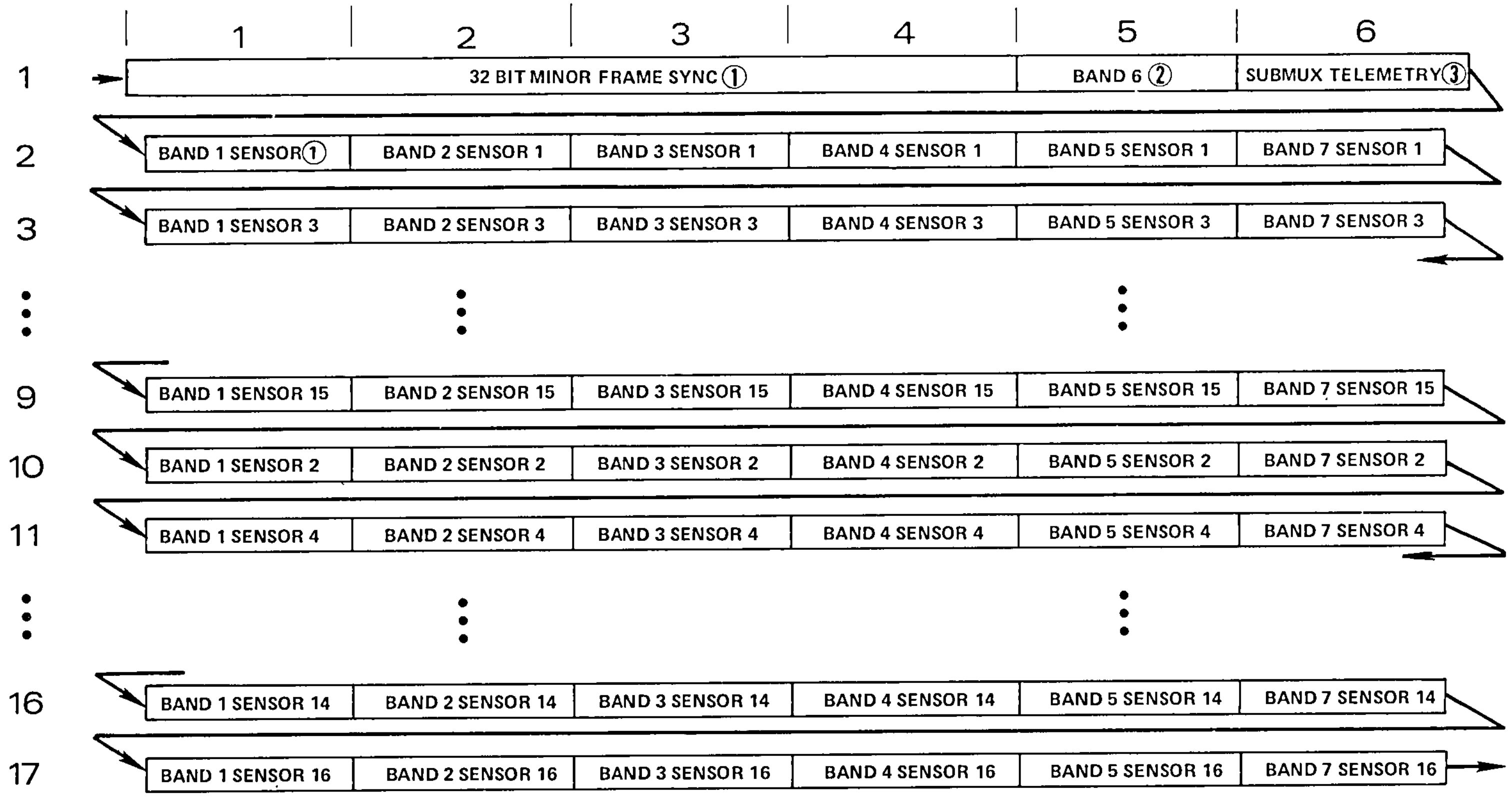

DIRECTION OF FLIGHT *
3.5 IFOV
25 IFOV
25 IFOV
25 IFOV
45 IFOV
26 IFOV
2.5 IFOV
16
15
2
1
14
13
12
11
10
9
8
7
6
5
4
3
[ORIG.]
BANDS
(NEW)
[1]
[2]
[3]
[4]
[7]
[5]
* USE BAND NUMBERS

Figure 7.

large ground distances between the bands and the staggered nature of the detectors within a band. Figure 7 shows the numbering arrangement within a band. Fiber optics were not used and the detectors themselves are mounted on the focal plane. Because of this and related reasons, the spacings are needed to help minimize cross talk. The mechanism and pattern of reading and transmitting the data is not commutated and converted in the same time-format as the MSS. Figure 8 shows the minor frame sampling format for the TM multiplexer. The data is acquired by tracking and holding each one-half (odd or even) detector-set for each band at a specific time thus the data is not a continuous time stream as in the MSS. The TM has a time-set for each half minor frame (odd or even numbered detectors) that is "photographic" in concept; i.e. all the detectors in that time-set are tracked and held and subsequently read out for a specific time.

The tracking period (dwell time) for each odd and even number detector set (all bands) actually is 9.611 microseconds, but the hold/read time for each occurs at alternating 4.81 microsecond intervals. The velocity of the ground trace in the cross scan direction is 3.12 meters per microsecond. Therefore, there is a 15 meter (3.12m/usec x 4.81 usec) locational difference between the odd and the even detectors when they are measured. This one-half IFOV or pixel in each band set. As shown in Figure 7, the odd-even between pixel spacing is 2.5 IFOVs. This 0.5 pixel difference results from time of results in a ground locational difference of either 2 or 3 pixels within a given band for odd and even detector, depending on direction of the sweep. Referring to Figure 7 and visualizing the ground pattern of these detectors moving from left to right (west to east), it is evident that if the odd-numbered detectors are measured first, when the even-numbered detectors in a given band are measured, they will have moved a half pixel closer to the area over which the odd-numbered detectors had been read. Thus, the ground location difference would be 2 pixels (2.5–0.5). If the sweep had been in the opposite direction (east to west), the even-numbered detectors would be spatially leading the odds, but the time sequence of measurement would be the same; i.e. odd numbers read first. The result is that for the east-west sweep, the even-numbered detectors would be effectively moving away from the area measured by the odd detectors. The result is that ground locational distance in this case would be 3 pixels (2.5 + 0.5). Figure 9 is a pictorial representation of this. Noting from Figures 6 and 7 the various interpixel distances involved, it is evident that a given time (To) for the odd-numbered detectors, the specific pixel distances between band 1 and 2 is 750 meters.

The same is true for band 2 to band 3, and band 3 to band 4. Band 4 and band 7 are 1,350 meters apart (45 IFOV), and band 7 and band 5 are 780 meters (26 pixels). Thus in a given minor frame, at time T_O, there is a fixed distance difference between the odd-numbered pixels of band 1 and those of band 5 (this encompasses the reflective or high resolution bands) of 4.38 kilometers. Before the odd-numbered detectors of band 5 look at the same ground pixel as band 1, they will go through 146 minor frames and cover all the intervening pixel areas (or vice versa). The relationship of the even detectors to these odd detectors will, in a given minor frame, depend on the direction of sweep. In each successive sweep the time sequence-location relationship is just 180° out of phase. So, when one builds an image of the pixels and considers a serial time stream of data, the reverse sweeps must be effectively flipped so that the cross-track relationships become the same. From the point of view of non-simultaneity of measurement of single pixel areas and the construction of a total TM 185 x 185 kilometer image (38 million pixels per reflective band), one can see the complexity of nonfixed time relationships for different locations within and among bands in a given TM scene.



① MINOR FRAME SYNC. =

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
0	0	0	0	0	0	1	0	0	0	1	1	0	1	1	1	0	0	0	1	0	1	1	0	1	1	0	1	0	0	0	1

② BAND 6 = SENSORS 1, 3, 2, 4 IN CHRONOLOGICAL ORDER.

③ SUBMUX TELEMETRY = 15 SPACECRAFT TELEMETRY WORDS, FOLLOWED BY ONE WORD OF MULTIPLEXER MAJOR FRAME COUNT.

Figure 8. Multiplexer Output Data Format.

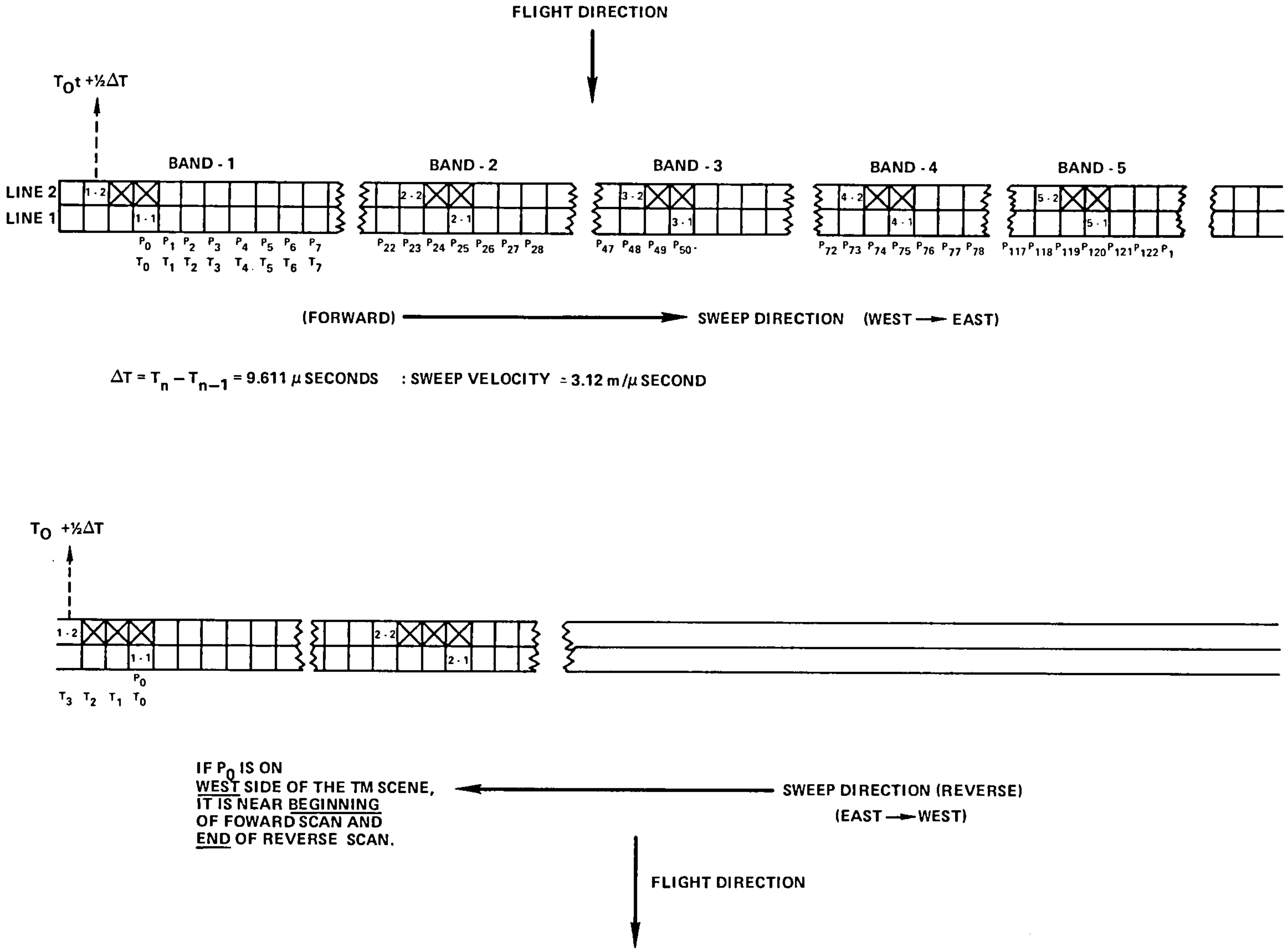

FLIGHT DIRECTION
T0t +½ΔT
BAND - 1
BAND - 2
BAND - 3
BAND - 4
BAND - 5
LINE 2
LINE 1
(FORWARD)
SWEEP DIRECTION (WEST → EAST)
ΔT = Tn − Tn−1 = 9.611 μ SECONDS : SWEEP VELOCITY ≈ 3.12 m/μ SECOND
T0 +½ΔT
IF P0 IS ON WEST SIDE OF THE TM SCENE, IT IS NEAR BEGINNING OF FOWARD SCAN AND END OF REVERSE SCAN.
SWEEP DIRECTION (REVERSE)
(EAST → WEST)
FLIGHT DIRECTION

Figure 9.

The thermal infrared (THIR) pixel area is 16 times the size of the other bands (120 meters x 120 meters). It is sampled at one-fourth the rate of the other bands (four minor frames to complete the sampling of all the thermal IR detectors). The interspatial relationships are as indicated in Figure 6.

It was noted above for the TM that each 48-detector subset (odds or evens) in a given minor frame is frozen at a fixed time within that minor frame. The MSS individual detectors were commutated in the analog mode, and each detector within a minor frame was sampled at a different time. They were digitized sequentially after this serial commutation, and all measurements went through to some A/D converter. The TM's larger number of detectors and the requirements for longer dwell times to improve the signal-to-noise ratio of the higher resolution, and narrower spectral bands do not allow this approach to be used in the Thematic Mapper. (The tracking time of the TM for each detector is 9.61 microseconds for one IFOV; as opposed to 0.398 microseconds for the individual MSS detectors.) During the subsequent hold period, the signal level of the detectors resulting from the tracking phase is read out by the multiplexer element supplied for each band. The eight detector outputs from each band are read by a given half of a minor frame and are A/D converted by an individual submultiplexer. Subsequently, the output of all these submux multiplexers is serialized by the main digital multiplexer. The result for a given minor frame is a digital stream of data and associated telemetry for all of the odd numbered detectors which would have been acquired at time To, and for all of the even number detectors which would have been acquired at a time, To + 4.81 seconds. Inasmuch as the planned aspect ratio of the TM cross-scan pixels of TM is 1:1; there is no double sampling of areas as with the MSS (as explained in Appendix A). Figure 10 shows the general layout of the TM multiplexer with its dual system.

To summarize the factors involved in understanding the relationship among the Thematic Mapper pixels and those that have to be considered in constructing an image from the data points:

1. The scanner sweep vectors that are 180° out of phase during each half-scan. All within-span relationships must take this into account.

2. At a given time, the various reflective bands may be looking at areas as far as 4.38 kilometers apart. To view the same ground pixel area that has been viewed by band 1, band 5 must look at 146 intervening pixel areas over a period of 146 minor frames. Random jitter or attitude changes occurring during this period could preclude it from even looking at the same ground pixel area; or even being aware of it.

3. The scan mirror-scan line corrector relationships must be known so that possible line-to-line overlap or underlap conditions can be accounted for and corrected.

4. The only parameter of commonality for keeping track of the pixels is the time of acquisition-system operation relationships. These must be accurately maintained and understood for the 2 billion plus bits of data per scene in order for usable data to be evolved.

SUMMARY

The foregoing explanations are an attempt to explain the jigsaw puzzle nature of scanner data and how the puzzle must be assembled to make geographic sense of the data. The key element to the

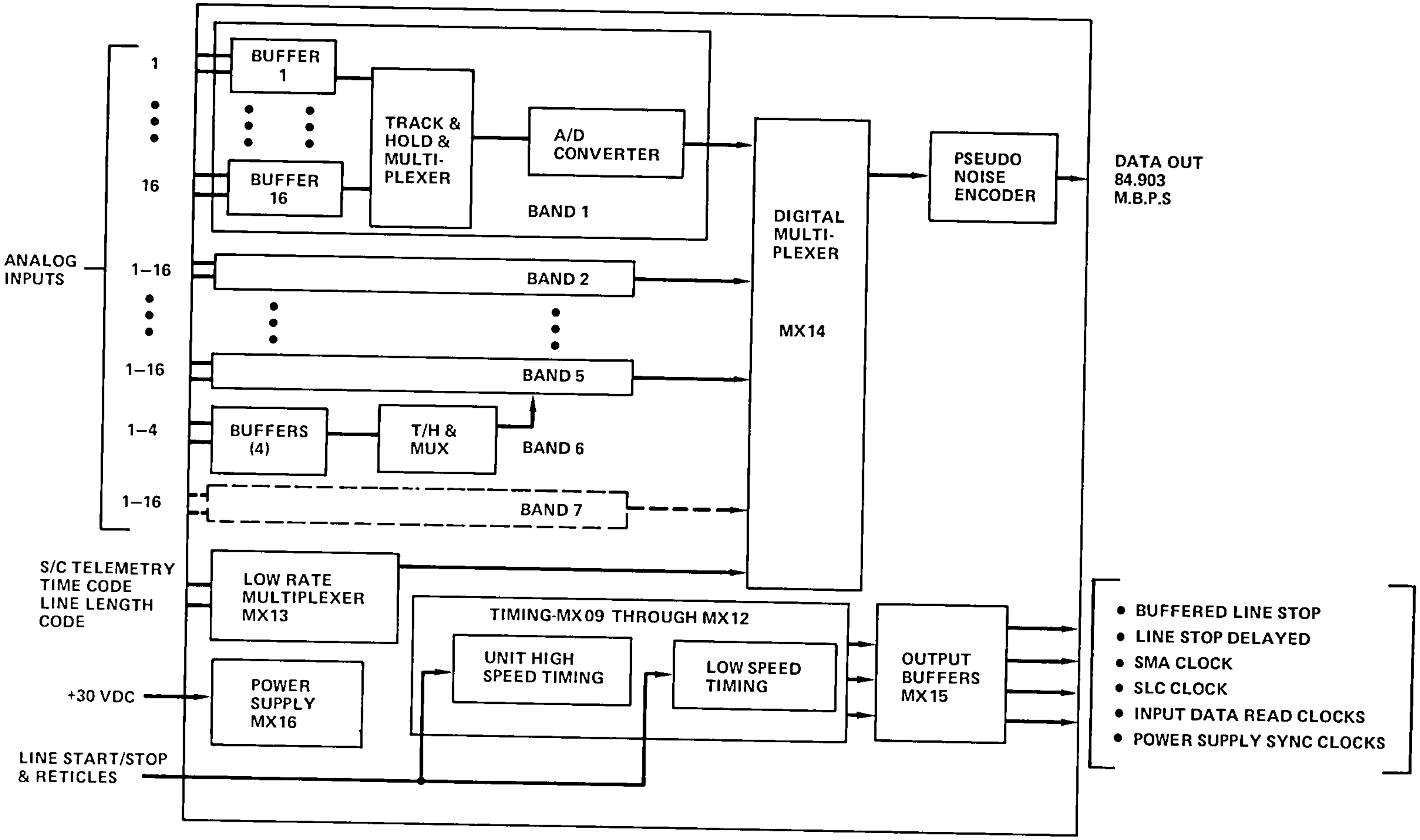

BUFFER 1
BUFFER 16
TRACK & HOLD & MULTI-PLEXER
A/D CONVERTER
BAND 1
1
16
ANALOG INPUTS
1–16
BAND 2
1–16
BAND 5
1–4
BUFFERS (4)
T/H & MUX
BAND 6
1–16
BAND 7
DIGITAL MULTI-PLEXER
MX14
PSEUDO NOISE ENCODER
DATA OUT 84.903 M.B.P.S
S/C TELEMETRY
TIME CODE
LINE LENGTH CODE
LOW RATE MULTIPLEXER MX13
TIMING-MX09 THROUGH MX12
UNIT HIGH SPEED TIMING
LOW SPEED TIMING
OUTPUT BUFFERS MX15
+30 VDC
POWER SUPPLY MX16
LINE START/STOP & RETICLES
BUFFERED LINE STOP
LINE STOP DELAYED
SMA CLOCK
SLC CLOCK
INPUT DATA READ CLOCKS
POWER SUPPLY SYNC CLOCKS

Figure 10.

assemblement of the pixels into data that is capable of being developed into information by the user, is time: time of acquisition and its relationship to the on-board processing and transmission system. The resultant scanner scene will be made up of millions of segments that have time as their locational key, but each pixel will have a time-space value that is different from every other pixel.

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APPENDIX A

For those who may not be familiar with the reason for the discrepancy between ground pixel equivalent size and that which might be expected from a square LIFOV, the following explanation is offered. Figure 2 shows the ground trace of measured segments as a line of segments or pixels 56 meters x 79 meters. The actual instantaneous field of view of the individual MSS scanner detector element in the focal plane is the area on the ground that subtends an angular field of view of 86 microradians (4.93 millidegrees). At a nominal altitude of 918 km the area IFOV is a square that is 79 meters on a side. In Figure A1a, T_0 represents this nominal field of view. The next time (T_1) that a given detector element is sampled is one minor frame later (9.96 microseconds). In this interval, the relative motion of ground to the viewing detector in the direction of scan is 56 meters (scan velocity = 5.61 meters/microseconds) x 9.96 microseconds. Figure A1b shows that this results in an area between pixels of 23 x 79 meters (1817 m^2) that is sampled twice. Figure A1c represents a segment of the cross-scan ground line of Figure 2. The measurement pixel which is 56 x 79 meters (4424 m^2) has a portion of it on each side (11.5 m x 79 m = 908.5) that is sampled twice. This is equal to overlap area indicated in A1b. This overlap area is about 41 percent of the total measurement pixel area (1817 ÷ 4424). This is usually described as having 1:1.41 aspect ratio in the direction of scan. In the perpendicular direction (roughly the direction of orbital motion) the field of views are designed to abut each other, that is they nominally have no overlap. In this direction, the aspect ratio is 1:1. In sampling theory there are desirable factors to oversampling. However, other system design considerations may preclude its use, as was the case in the oribtal direction of Landsat. The thematic mapper of Landsat-D is designed to have a 1:1 aspect ratio in both directions.

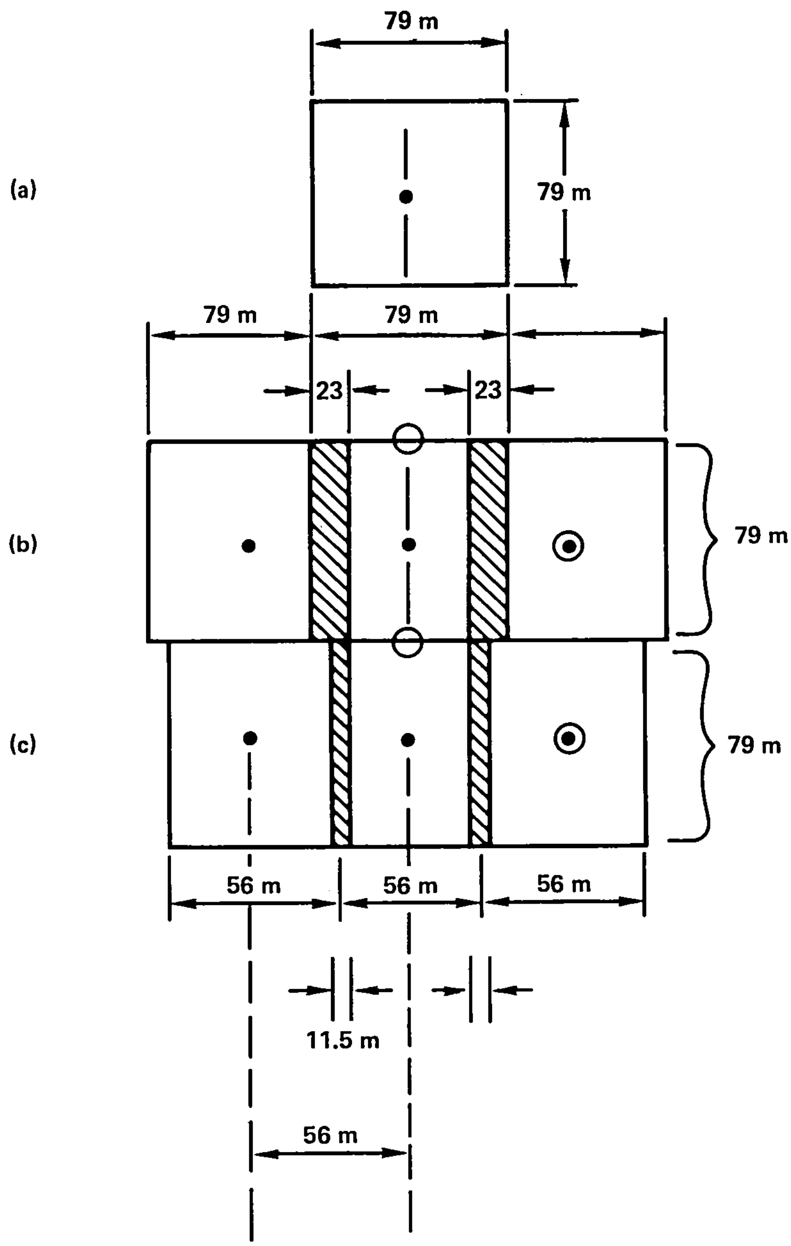

Figure A-1.

APPENDIX B

The general function of the Scan Mirror Assembly (SMA) in the TM is identical with that of the MSS, to provide a continually changing view by the sensors across the direction of flight of the spacecraft. This action, coupled with the orbital motion the spacecraft itself, provides the matrix that goes into providing a 2-dimensional scene. In the MSS, the SMA motion coupled with flight motion was adequate to accomplish this because you have active sweep in one direction only. As explained in the text, this is not so with the TM. The scan motion must also be modified to achieve an effective cross-track motion that is perpendicular to the line of flight. The means of accomplishing this is the scan line corrector optics (SLC). Figure B1 is a simplified diagram of the optics of the TM. Figure B2 is a schematic representation of the action of the SMA. The diagram is facing northward, and the direction of flight would be outward from the page. If we consider the ground elements A_n as series of pixels observed by a given detector D1, we see that as the SMA moves through an angle α, the ground trace moves through an angle of $2\alpha = B$. Unless altered, this motion would describe the ground pattern shown in Figure 4 of the main text, except that it would have 16 lines for the TM. If we insert a set of parallel minors whose axis of rotation is roughly perpendicular to that of the SMA, we introduce a vector motion that translates the observed pixel northward as we go in either direction across the scan. The effect is that a given detector is following an across-scan trace that is the result of these two motions. Combining Figures B2 and B3 and looking backward from the detector, it is evident that the action of the SLC effectively is moving the point of vision in the plane of the SMA mirror into the paper in Figure B1 as A_n sweeps from A1 to A2 or vice versa. (For a more detailed explanation of the optics see ref. 6.) Note that as the active motion of the SLC mirrors must always be in the same direction no matter what the sweep direction of the SMA mirror, the effective angular rotation rate of the SLC must be twice that of the SMA.

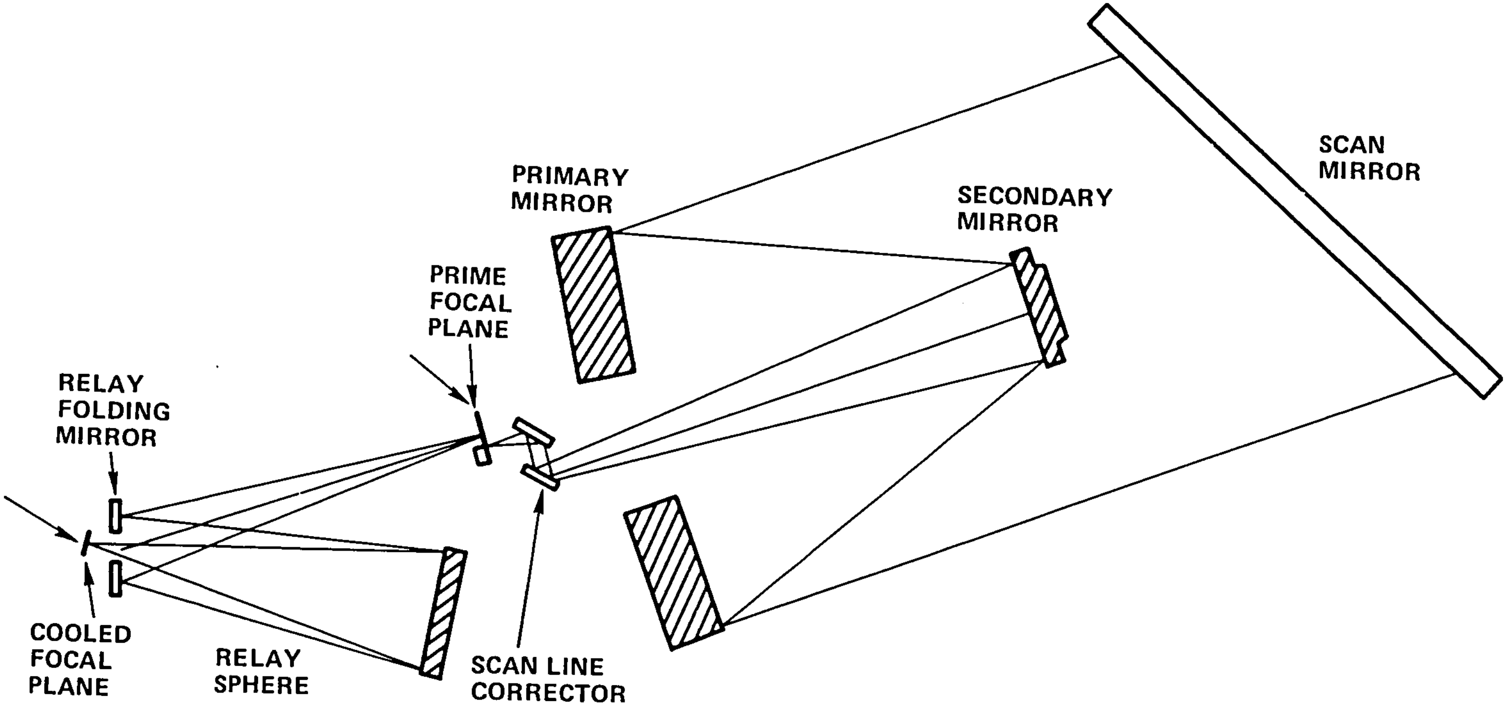

Figure B-1. Optical System Elements.

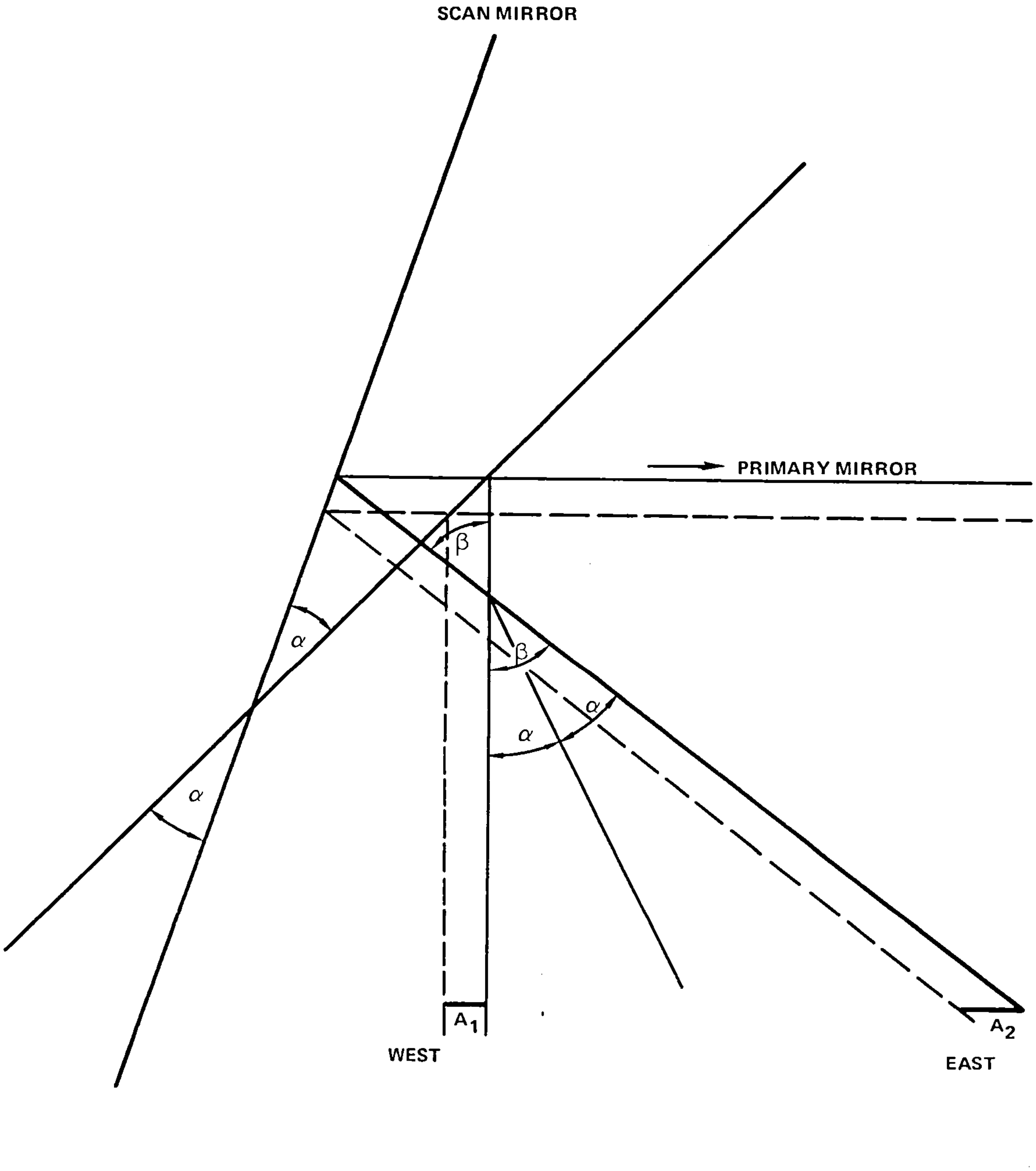

Figure B-2.

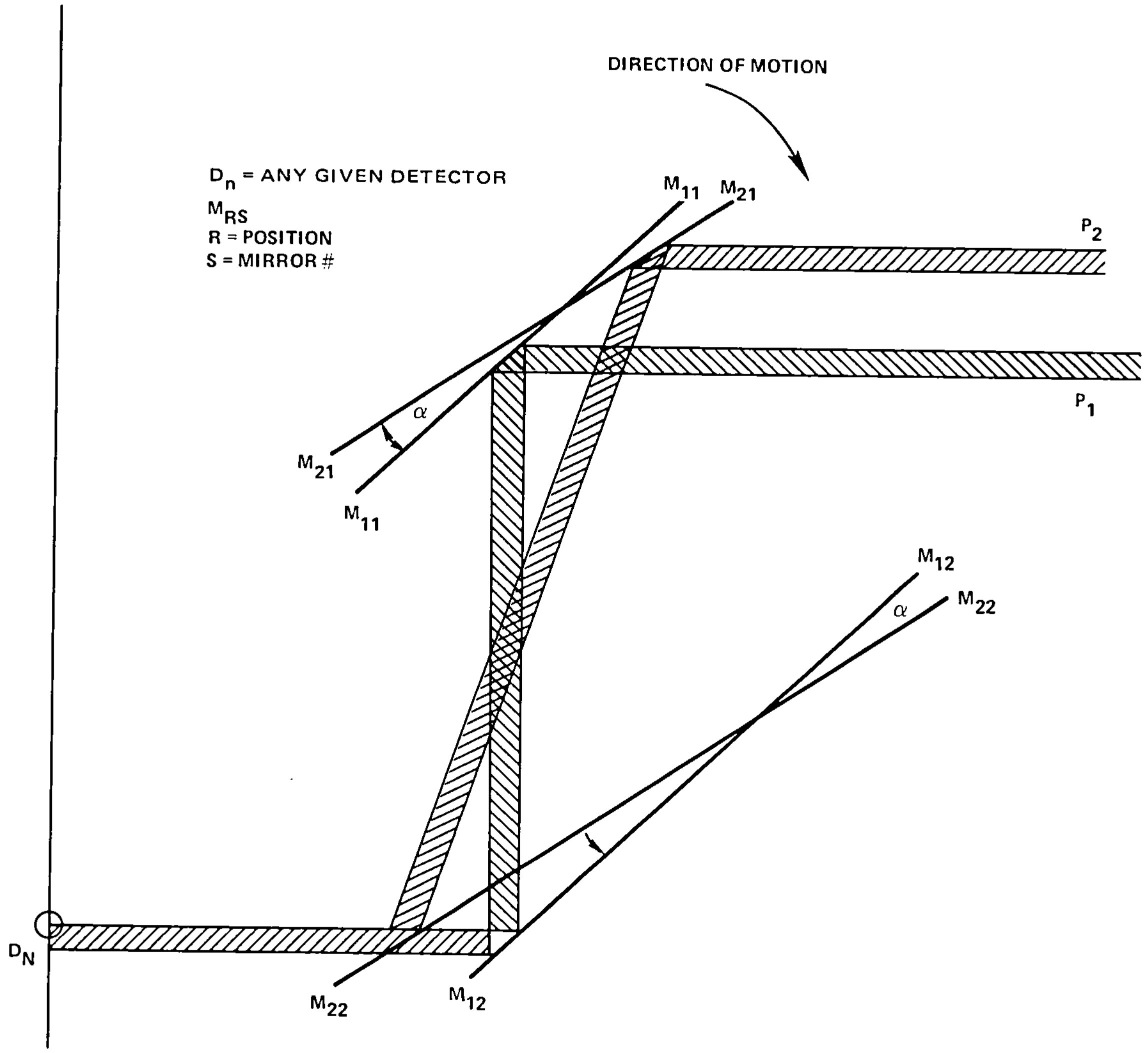

Figure B-3 Scan Line Corrector.

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15. Supplementary Notes

16. Abstract

Many users of scanner data do not understand the time-space relationships among the data points (pixels) of this type data. There is often a tendency to conceive this data as being acquired in the unit-time mode, as is the case with "photographic" data. This paper is an attempt to offer a simplified explanation of just what are the time-space relationships among scanner pixels by describing these relationships as they occur in the Landsat multispectral scanner (MSS) and the Landsat-D Thematic Mapper (TM).

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