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# Remote Sensing Using Solid-State Array Technology*

## Linear arrays provide precision geometric positioning of the detectors, very high sensitivity and favorable signal-to-noise ratio, low power consumption, and no moving optics.

Abstract: *Current multispectral remote sensing of the Earth's surface from satellite platforms requires sensor systems which use mechanically moving mirrors, as in the Landsat Multispectral Scanner* (MSS) *and the upcoming Thematic Mapper* (TM). *The* TM *with its 30 metre ground sample distance is a complex sensor system which requires manufacturing tolerances of tenths of a micrometre and mechanical control of the scanning mirror to arc seconds. For future applications which require high resolution (10 m region) and/or narrower spectral bands in the 0.4 to 1.1 μm region without sacrificing sensitivity, a sensor system which uses solid-state linear arrays and operates in a "pushbroom" scan mode can provide the required performance. In the pushbroom scan mode, the line array of detectors is oriented perpendicular to the ground track velocity. As the along track motion scans the projection of the detectors over the scene, the detectors are electronically sampled in such a way that the entire line array is read-out in the time to advance one resolution element. The advantages of line arrays include precise geometric positioning of the detectors; very high sensitivity and favorable signal-to-noise ratio* (S/N) *with small lightweight optics; low power consumption; and no moving/oscillating optics. Laboratory experiments using straightforward techniques show that the precision radiometric calibration of thousands of detectors is possible. In addition, it has been demonstrated that multiple monolithic linear array devices (chips) can be assembled together to provide linear arrays with thousands of detector elements. Alignment tolerances of better than 0.3 resolution element have been achieved, and techniques have been described to improve this to 0.1 resolution element. System level noise performance has been demonstrated which allows a sensor system to be provided with 10 metre ground sample distance and with noise equivalent reflectance better than the Thematic Mapper at 30 metres.*

### Background

Since the first weather satellites began to image cloud patterns and to provide a synoptic view of the Earth's surface, we have been evolving ever more sophisticated sensors to help unlock the basic information in the upwelling radiance from the lands and seas. In the early 1960s, simple TV type pictures were provided. Cloud shapes and relative motions were evident, but radiometric information could not be provided by these imaging sensors. The radiometers which were built at this time required reso-

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lutions* on the order of kilometres (Goldberg, 1968; Ostrow, 1970) in order to provide the requisite sensitivity to small changes in the target radiance.

In 1972, NASA launched the first "Earth resources" sensors into orbit (Landsat-1) and a quantum leap in resolution from approximately one to better than 0.1 kilometre was accomplished. The success of the Multispectral Scanner (MSS) and Return Beam Vidicon (RBV) sensors has been widely acclaimed. Today, 1978, these basic sensor technologies remain representative of the remote sensing capabilities from satellite platforms.

In 1977, NASA initiated new technological developments to enhance and upgrade remote sensing from satellite platforms. An evolutionary growth of the electro-mechanical scanner technology embodied in the Landsat MSS is now under development. This sensor, the Thematic Mapper (TM), is being constructed for launch in 1981. Compared to the MSS (79m IFOV,† 4 bands, 64 gray levels) the Thematic Mapper will provide improved spatial resolution (30m IFOV), additional and narrower spectral bands (seven), and increased instrument sensitivity (256 gray levels). This last improvement is equivalent to going from roughly 2 percent precision to 0.5 percent precision. As

* Resolution as used in this article refers to the geometric footprint of the sensor due to the field-stop of the optical system, usually the detector aperture.

† Instantaneous field-of-view.

significant as the Thematic Mapper's performance improvements are, they still represent a limitation. As shown in Figure 1,* the electro-mechanical scanners have reached a plateau in development. Any further improvements in performance will be increasingly costly for only small increments in performance ability.

## PUSHBROOM SCAN TECHNOLOGY

NASA/Goddard has had under development since the early 1970s a sensor technology that allows a second quantum leap in performance for remote sensing. This new generation of sensor operates on a principle different from the electro-mechanical scanners.

Pushbroom scanning is a term which describes the technique of using the forward motion of a satellite platform to sweep a linear array of detectors oriented perpendicular to the ground track across a scene being imaged. This technique is illustrated in Figure 2, which shows an optical system imaging the ground scene on a line array of detectors. One array is typically used for each spectral channel. Satellite motion provides one direction of scan and electronic sampling of the detectors in the crosstrack dimension provides the orthogonal scan component to form an image. The detector array is sampled at the appropriate rate so that contiguous lines are produced.

* The Merit Function of Figure 1 is explained in Appendix A.

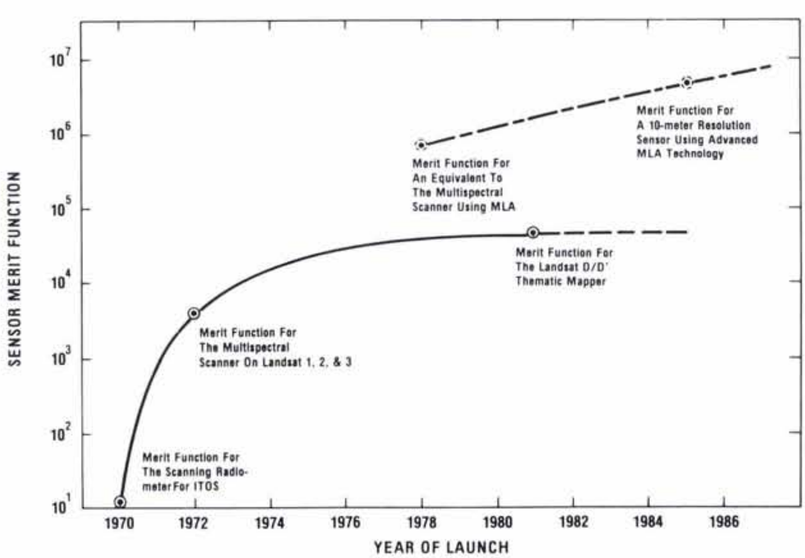


FIG. 1. Historical trend in Earth-viewing electro-mechanical scanners.

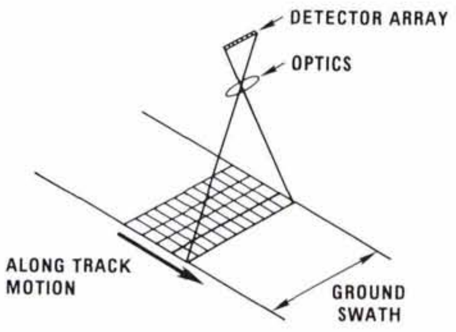


FIG. 2. Geometry of pushbroom scan technique.

There are two principal advantages to the pushbroom scan techniques using long linear arrays of solid-state detectors. First, complex mechanical scan mechanisms are eliminated. Second, this approach allows the photon flux from the scene to be integrated during the time required for the instantaneous field-of-view (IFOV) to advance the dimension of one resolution element on the ground. For a quantitative indication of what this means, consider that the dwell time per resolution element in the Landsat Multispectral Scanner (MSS) is 14 microseconds. Using the pushbroom approach and the same orbital conditions, the dwell time can be increased to approximately 12 milliseconds for the same resolution element dimensions. This allows an increase of more than a factor of 800 in the signal generated and stored at each detector position. The improvement in signal-to-noise ratio is significant, and permits smaller aperture optics to be used, with a consequent reduction in size and weight.

Another advantage of solid-state technology is that high cross-track geometric fidelity is achieved along each linear array to the extent that the position of each individual detector is precisely known. Spacecraft motions limit the ability to attain geodetic fidelity along track, but corrections for attitude during ground data processing should reduce the variations in effective ground distance between successive scans to a minimum. Besides the geometric accuracy within a single array, accurate positioning of arrays for each spectral band in the image plane with respect to each other allows very close multispectral registration of the resulting images.

It is clear that operation in a pushbroom scan mode has many desirable features. The trick is now to provide the many thousand element detector arrays required to subtend the crosstrack swath for Earth resource applications. Typically a 30-m resolution pushbroom sensor requires 6300 detectors per spectral band to subtend a Landsat type swath. Imagine the complexity and cost of providing this large an array with 6300 individual point detectors, each with a wire bond to discrete amplifier components. Each signal channel (detector) would have in excess of 30 components associated with it, giving almost 200,000 parts per band and 800,000 parts per instrument. There has to be a better way.

Solid-state integrated circuit technology provides the answer. On a single monolithic chip of silicon, hundreds to over a thousand detectors can be manufactured. In addition, low noise "on-chip" amplifiers and electronic multiplexing circuits are provided simultaneously. By manufacturing all these elements on a single integrated circuit, it is now possible to have an array of hundreds of detectors which interface to the rest of the world with only a few wire bond connections. Figure 3 shows one approach to array organization to illustrate how the detector signals are sampled and read off the chip. Each detector is sequentially connected, one at a time, to an on-chip amplifier. A circuit called a dynamic shift-register controls the sequence of the connections to the amplifier. This approach allows a relatively small area of the array to be dedicated to low noise analog signals, and a different area of the chip to be used for digital switching operations. The yield (the number of working devices out of the total lot) of solid-state devices is directly proportional to the area of a chip. Digital circuits are relatively more fault tolerant than analog elements. Minimizing the area devoted to low noise analog signals improves the yield of detector array chips and, thus,

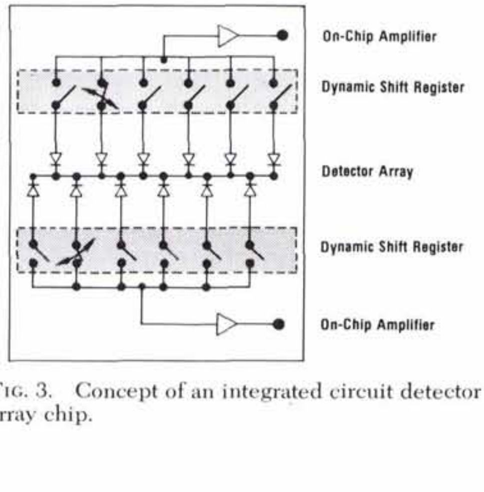


FIG. 3. Concept of an integrated circuit detector array chip.

should lower the cost per detector. There are other chip architectures which have different desirable features (NASA, 1972). The point is that solid-state integrated circuit technology provides the means to deliver large linear arrays for pushbroom scan sensor systems.

NASA/Goddard Space Flight Center, through a contract with Westinghouse Electric Company (Westinghouse, 1976), developed a detector array technology which demonstrated performance adequate for a 10-metre resolution multispectral imaging radiometer. The work started in 1972 and was completed in 1976. This work with Westinghouse provides the foundation for the decision to pursue a program to develop a space qualified multispectral remote sensing instrument using solid-state linear arrays.

## Performance of Pushbroom Systems

### Radiometric Sensitivity

What I would like to do now is to determine the required performance to provide 0.5 percent sensitivity in four spectral bands for a variety of scene conditions, and then show how well a pushbroom scan sensor with 10 metre "resolution" meets these requirements. The spectral bands chosen are the visible/near IR bands of the Thematic Mapper. Let me, in addition, define 0.5 percent sensitivity as the change in target reflectance ($\Delta\rho = 0.005$) equal to the RMS noise of the sensor system. This is the noise equivalent reflectance, $NE\rho$.

First, take a scene condition (Fraser, 1975) that roughly corresponds to summer in the southern United States. The solar angle to the zenith is 10°, and the atmosphere approximates a clean rural condition (visibility = 27 km) (Table 1). The time of day is 10:30 A.M.

The second scene condition is more stringent. It corresponds to spring or fall in central Canada. The solar angle to the zenith is 45°, and again the atmosphere has 27 km visibility (Table 2). I have lowered target reflectance, also.

Table 1

| | Spectral Band ($\mu$m) | Target Reflectance | Scene Radiance (w/m²-sr) | Required S/N* |
|---|---|---|---|---|
| (1) | 0.45 – 0.52 | 0.10 | 7.0 | 52 |
| (2) | 0.75 – 0.60 | 0.20 | 9.8 | 65 |
| (3) | 0.63 – 0.69 | 0.20 | 6.0 | 57 |
| (4) | 0.75 – 0.91 | 0.50 | 24.6 | 117 |

* To provide $NE\rho = 0.005$.

Table 2

| | Spectral Band ($\mu$m) | Target Reflectance | Scene Radiance (w/m²) | Required S/N* |
|---|---|---|---|---|
| (1) | 0.45 – .52 | 0.02 | 3.0 | 38 |
| (2) | 0.52 – .60 | 0.10 | 4,4 | 48 |
| (3) | 0.63 – .69 | 0.10 | 2.3 | 35 |
| (4) | 0.75 – .91 | 0.20 | 7.0 | 52 |

* To provide $NE\rho = 0.005$.

The following parameters describe the salient characteristics of the pushbroom scan sensor which will attempt to meet the requirements in Tables 1 and 2. Assume a nominal orbital altitude of 700 km:

Optics Aperture: 30 cm
Focal Length: 105 cm
Instantaneous field-of-view: 14.3 $\mu$rad
Optical Transmission (Filters included): 0.3
Signal Integration Time: $1.50 \times 10^{-3}$ seconds

To complete the characterization of this sensor, assume now a very conservative noise level of 1000 electrons RMS.*

In the current technical literature noise levels of 100 to 200 electrons RMS are routinely reported, and have been for several years (White, 1974). Table 3 lists the noise level for each spectral band in units equivalent to exposure density at the focal plane. Remember, the detectors integrate photon flux from the scene in the pushbroom scan mode.

NOTE: Area of Detector = $14\mu m \times 18\mu m = 2.7 \times 10^{-10}$ m²

Quantum Efficiency = 0.7 (bands 1-3)
0.5 (band 4)

With the above parameters the signal-to-noise ratios listed in Table 4 are provided in each spectral band for the conditions of Tables 1 and 2.

Table 3

| Spectral Band No. | Noise Equivalent Signal ($10^{-6}$ J/m²) |
|---|---|
| (1) | 2.19 |
| (2) | 1.81 |
| (3) | 1.59 |
| (4) | 1.77 |

* This level of noise was measured in 1972.

TABLE 4

| Spectral Band No. | S/N Table 2 Required | S/N Pushbroom | S/N Table 1 Required | S/N Pushbroom |
|---|---|---|---|---|
| (1) | 38 | 38 | 52 | 88 |
| (2) | 48 | 68 | 65 | 145 |
| (3) | 35 | 41 | 57 | 103 |
| (4) | 52 | 107 | 117 | 339 |

Table 4 shows that a pushbroom scan sensor can indeed provide the required performance at 10 metre resolution. In addition, if either 500 electrons noise or an increase in quantum efficiency to 0.95 or a combination are used (as would be appropriate for current array technology), then spectral bands as narrow as 20nm wide could be used in the sensor's design. As a matter of comparison to the Thematic Mapper, with its 30 m resolution and 42 cm optics aperture, Table 5 is provided (for Table 2 conditions).

Another way of showing sensor performance at different scene conditions is shown in Figure 4. Based on previous definitions, this figure is self-explanatory.

### DETECTOR ARRAY GEOMETRIC FIDELITY

Figure 5 shows an array assembled under the Westinghouse program. Using 18 silicon chips, each with 96 detectors, an array of 1728 detectors was provided. Although current technology can now provide single chips with over 1000 elements, this illustration serves to show how arrays of 6000 or more detectors (as needed in a Thematic Mapper application) could be assembled. The detector positions on each chip are precision controlled to 0.05 of a resolution element. The chips in the 18-chip array were aligned to a precision of 0.3 of a resolution element size with a cumulative error over the length of the array of 0.5 of a resolution element. The depth of focus was controlled to $\pm$ 12 $\mu$m.

The advantage of the approach shown here is that the edges of these array chips are precision manufactured to allow contiguous (!) alignment of detector elements on a chip-to-chip basis. Ground data processing is simplified. Other suggested approaches end up with a bi-linear configuration where the chips are spatially staggered over distances equivalent to 200 resolution elements. Another advantage of a segmented contiguous array is that cordwise approximation to curved focal surfaces are permitted. In high resolution systems, this may be required. The singular disadvantage of the contiguous approach is that typically one 15 $\mu$m space is required at the chip edges. This is equivalent to having a dead element in the array. This may or may not be a significant disability depending on the application under consideration.

TABLE 5

| Spectral Band No. | S/N Pushbroom | S/N Thematic Mapper |
|---|---|---|
| (1) | 38 | 35 |
| (2) | 68 | 72 |
| (3) | 41 | 45 |
| (4) | 107 | 122 |

### RADIOMETRIC CORRECTION

Perhaps the single most frequent concern regarding pushbroom technology is the question, "How are you going to destripe the data from *thousands* of detectors, when you have problems with the 24 detectors on the Landsat Multispectral Scanner (MSS)?" I would like to let a picture speak for itself.

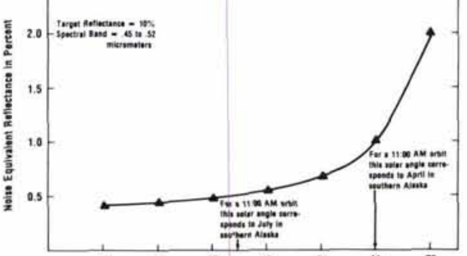


FIG. 4. Noise equivalent reflectance versus solar zenith angle for a system with a 10 m IFOV using current detector technology and 21 cm optics.

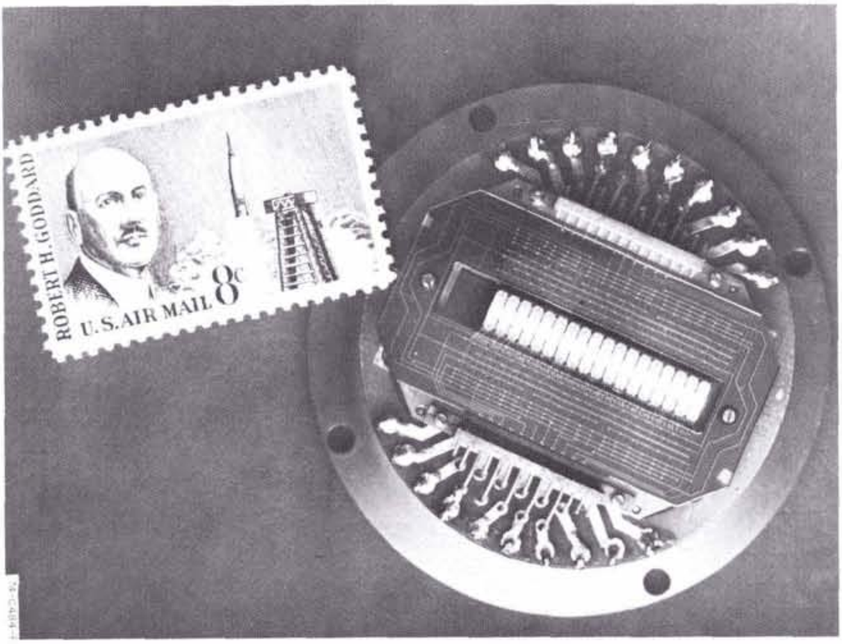


FIG. 5. A 1728-element detector array manufactured from 18 individual integrated circuit chips. The detector array is the dark line at the center of each chip.

Figure 6 shows a positive print of a radiometrically corrected image made using the 18-chip array on a laboratory scene simulator. A USGS high resolution black-and-white transparency was back illuminated, spectrally filtered, and then imaged into the array. The image format is 1728 by 1728 lines per picture width. The full scale spectral radiance level corresponds to Band 4 in Table 1. The integration time was 1.44 millisecond (roughly that for 10 metre resolution on a satellite). The furrows in the field in the pictures center are approximately two resolution elements center-to-center.

FIG. 6. Example of a radiometrically corrected image made with the 18-chip array. Direction of scan is top to bottom.

Careful examination is required to determine the direction of scan. The tip-off is some line structure where a dead element was cosmetically corrected by averaging between adjacent working elements. Regardless, a good job of radiometric corrections has been achieved. To show that this one image is not a fluke, Figure 7 shows a montage of four separate pictures whose individual image format is 576 by 576 lines per picture width. Again, radiometric correction has removed the detector-to-detector variations.

The critical elements in radiometric correction of detector arrays are

- Provide a highly stable operating temperature at the array, and stable bias voltage;
- Provide updates of calibration files at the beginning of an orbital pass and at the end to determine if any drifts have occurred;
- Have an extensive ground calibration procedure to catalog array performance under various bias voltage and focal plane temperature configurations; and
- Plan to have most elements corrected using a simple equation of a straight line. For the other elements, either linear segment approximations with five or more calibration points per detector or some

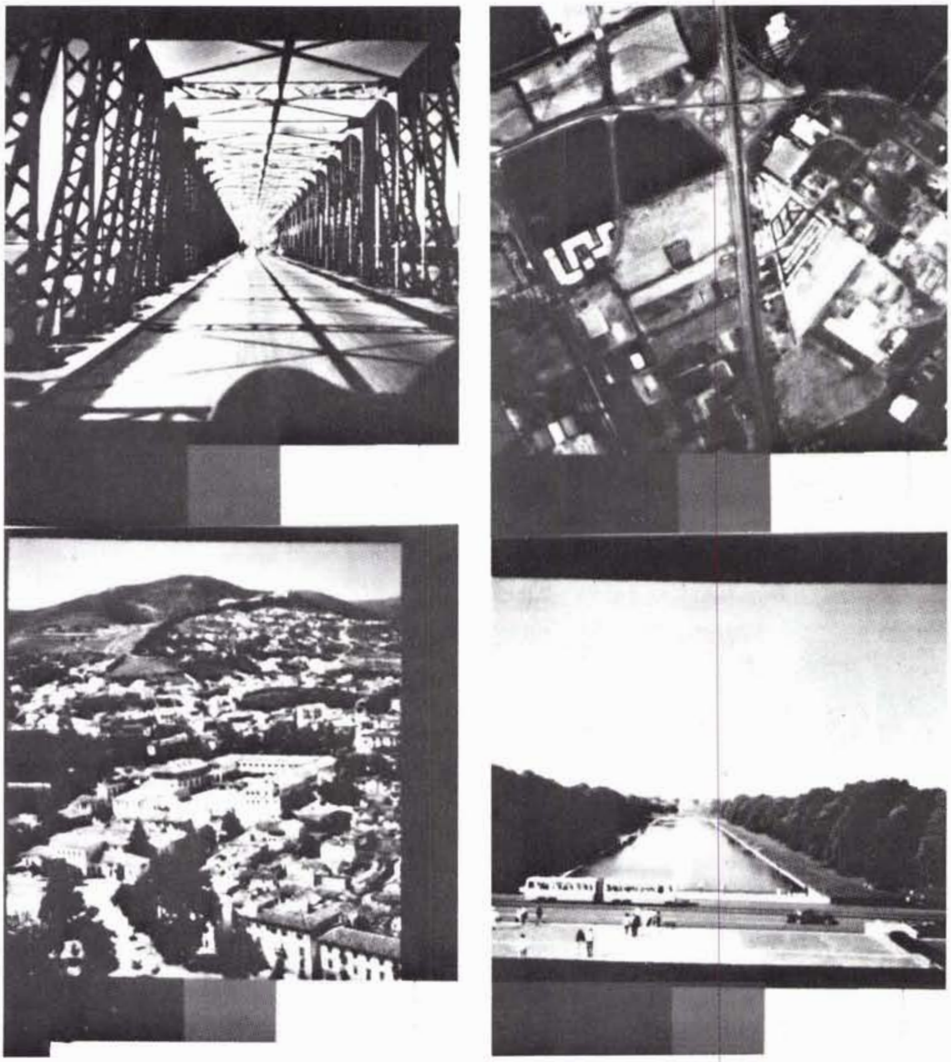

FIG. 7. Examples of radiometrically corrected imagery from a 576-element detector array.

complex polynomial fit will be required. Good software is required to do the job efficiently.

## CONCLUSION

For the visible/near IR spectral region, silicon pushbroom scan arrays have matured and are ready for application to remote sensing from satellites. Significant performance is available, and can be used to provide a wide range of configurations optimized for specific applications. Figure 8 shows one sensor concept. This sensor can be used for agricultural multitemporal sampling. This sensor provides two to five day return coverage to any place on the Earth's surface and stereographic imaging for topographic mapping.

Extension of the spectral response of arrays into the 1 to 5$\mu$m and 8 to 14$\mu$m region will be developed over the next four years under NASA contracts. The military has provided the technology base, and we will attempt to optimize that base for our applications. A positive view of the future indicates we will be ready in 1984, and a first launch of a pushbroom scan sensor with all the spectral bands of the Thematic Mapper is anticipated by 1988.

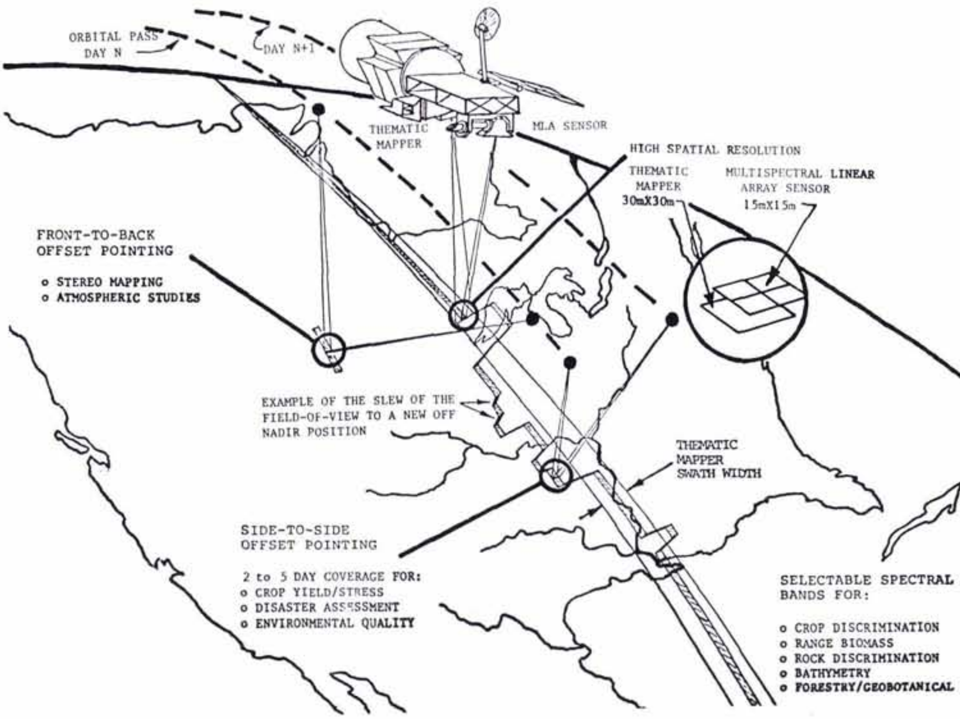


FIG. 8. Concept of a multispectral linear array sensor (MLA) which provides agricultural repeat coverage and stereo.

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## APPENDIX A

### Merit Function for Historical Trends in Sensor Development

First, any merit function used should increase in numerical value with improvements in performance. Secondly, the inputs to the merit function should be based on factors that are generally accepted as indications of improved performance. To this end, the factors considered include

- Resolution (in terms of angular subtense),
- Number of spectral bands,
- Spectral bandwidth,
- Signal-to-noise ratio for a specific spectral radiance that is used as a common input to each of the selected systems.

In order to develop the desired merit function for sensor systems, we start with the equation for calculation of signal-to-noise (S/N);

$$\text{S/N} = \frac{\pi(D_0^2)\ (\text{IFOV})^2\ (\tau_0)\ (N_\lambda)\ (\Delta\lambda)}{4\ (\text{NEP})}$$

where, $D_0$ is the optics diameter, IFOV is the instantaneous field-of-view, $\tau_0$ is the effective optics throughput, $N_\lambda$ is the spectral radiance, and $\Delta\lambda$ is the spectral bandwidth. The numerator calculates the radiant power at the detector, and the denominator expresses the system noise as the radiant power at which the S/N equals one (Noise Equivalent Power, NEP).

The next step is to rewrite the equation above as a proportionality statement:

$$\frac{1}{\text{NEP}} = \frac{\text{S/N}}{(D_0^2)\,(\text{IFOV})^2\,(\Delta\lambda)}$$

System sensitivity measured in NEP is an important indication of performance, and the inverse gives a numerically increasing factor for improvements in performance (i.e., NEP becomes smaller).

This is the basic merit function. However, I want to expand this relation to include factors that indicate the increasing sophistication of sensor systems. The first additional factor is to make the relation directly proportional to the number of spectral bands. Next, consider scan efficiency. As the years have gone by, we have worked very hard to increase scan efficiency. The merit function is made directly proportional to this factor. Lastly, it can be shown that the mechanical scanners' optical systems do not operate anywhere near the diffraction limit in the visible spectrum, in terms of IFOV size compared to the diffraction blur size for the optics diameter provided. This has been the case because increased optics diameter was required to provide the specified S/N. To consider the penalty of increased sensor size to provide the required sensitivity, I now modify the $(D_o^2)$ term to become the sensor density (total weight divided by telescope volume).

The Merit Function for visible spectral band performance can now be written

$$(\text{Merit Function})_{\text{vis}} = \frac{\text{S/N}\;(N)\,(WT)\,(\eta) \times 10^{-11}}{(D_0^2)\,(FL)\,(\text{IFOV})^2\,(\Delta\lambda)}$$

where the new terms in the expression are $(N)$, the number of spectral bands; $(WT)$, the sensor weight; $(\eta)$, the scan efficiency; and $(FL)$, the optics focal length. The multiplying constant is used as a matter of convenience to scale the ordinate.

## Notice to Contributors

1. Manuscripts should be typed, double-spaced on 8½ × 11 or 8 × 10½ white bond, on *one* side only. References, footnotes, captions—everything should be double-spaced. Margins should be 1½ inches.
2. Ordinarily *two* copies of the manuscript and two sets of illustrations should be submitted where the second set of illustrations need not be prime quality; EXCEPT that *five* copies of papers on Remote Sensing and Photointerpretation are needed, all with prime quality illustrations to facilitate the review process.
3. Each article should include an abstract, which is a *digest* of the article. An abstract should be 100 to 150 words in length.
4. Tables should be designed to fit into a width no more than five inches.
5. Illustrations should not be more than twice the final print size: *glossy* prints of photos should be submitted. Lettering should be neat, and designed for the reduction anticipated. Please include a separate list of captions.
6. Formulas should be expressed as simply as possible, keeping in mind the difficulties and limitations encountered in setting type.