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Sensor Implications of High Altitude Low Contrast Imaging*

Time delay and integration (TDI) mode detectors—area devices used in a linear fashion—collect large amounts of signal with low noise operation and high responsivity.

THE USE OF linear solid state detector arrays for primary data acquisition in remote sensor applications has generally been limited by the performance characteristics of detector devices which have been developed with a broad variety of applications in mind. The experiment designer has therefore been constrained with respect to several important data collection parameters.

In general, the sensors have operated in the "strip" mode, where motion of the vehicle provides picture generation in one dimension (along track) and electronic readout of the detector(s) provides picture generation in the second dimension (cross track).

While classical general purpose linear detectors (such as self-scanned diode arrays, CCD arrays, etc.) have done a remarkably good sensing job, all things considered, it is reasonable that, with the increased emphasis now being placed on earth resource exploitation, the unique detector requirements associated with high altitude remote sensing be given special attention.

The specific operating features which are desired in a remote sensing detector (as differentiated from a general purpose one) may be summarized as follows:

- It must be able to perform under conditions of extremely low apparent image contrast. This implies the ability to collect large amounts of signal.
- It must operate under conditions of low illumination (low sun angle). This implies low noise operation.
- It must exhibit a high level of responsivity throughout the NASA "multispectral" wavelength domain from 500 thru 1100 nanometres.

These general characteristics may be translated into specific detector performance specifications for any fully defined system operation requirement. However, since the nature of this communication is more general, we will deal here with broad parameters, using specific characteristics by way of example.

The first two of the above disiderata are closely intertwined insofar as their implications for detector design are concerned. The first requires the ability to collect a large amount of signal from the scene, and the second requires performance when little signal is available. When the two requirements are combined, there is an obvious need for detectors of unusual capability.

In scenes of low apparent image contrast, it is necessary to post-process the video data in order to remove from it the general D.C. background level and, perhaps, the very low spatial frequency brightness variations as well. After such removal, the remaining A.C. signal can be amplified and displayed, provided, of course, that unwanted signal variations have been compensated beforehand. These operations form the basis of the "fog and haze" removal aspects of the remote sensor system.

In order for such image processing to be effective, however, it is necessary to maintain the system signal-to-noise ratio (S/N) above some selected limiting value. Otherwise, only empty amplification (the equivalent of empty magnification in optical image assessment) will result. If, for example, one selects a tri-bar target resolution criterion, an S/N value of 3.6:1 between a bar and a space might prove appropriate (Wight, 1977).

Since the original point of generation of signal electrons within the detector is the one at which the minimum number of "events" occurs, it is appropriate to determine the "noise in signal" there. If the 3.6:1 S/N ratio is adopted, the required number of electrons (k) per resolution element (bar or space) may be derived from the expression:

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* Presented at the ACSM/ASP Annual Convention, March 1978, Washington, DC.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 45, No. 1, January 1979, pp. 63-66.

$$\sqrt{k} = \frac{3.6\sqrt{(R_t/R_b) + 1}}{(R_t/R_b) - 1} \qquad (1)$$

where R_t and R_b are the reflectivities of the target and the background respectively.

The relationships among reflectivities, contrast ratios (apparent at the entrance pupil of the sensor), and the number of electrons required (k) are presented graphically in Figure 1.

For example, if one encountered the situation where

$$R_b = 0.50 \text{ and}$$
$$R_t = 0.51, \text{ then}$$
$$\text{Contrast Ratio} = \frac{0.51}{0.50} = 1.02{:}1$$

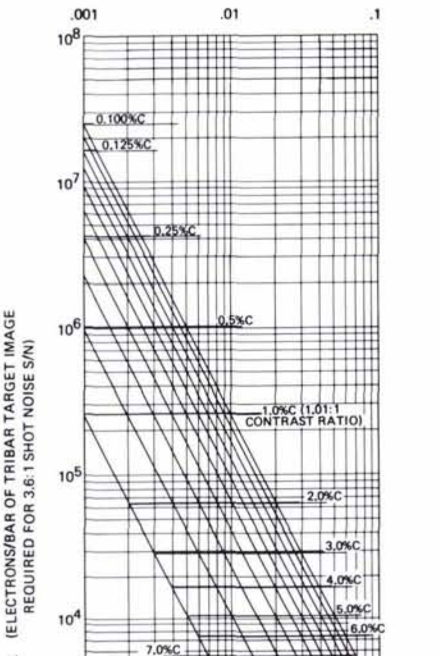

FIG. 1. Relationships among background reflectance, target reflectance, and contrast as these influence the number of photo electrons necessary to yield useful shot noise limited performance.

The number of electrons (k) needed for a 3.6:1 shot S/N is approximately 62,000. This is the requirement based upon shot noise only, and does not consider other system noise sources. These other noise sources must be root sum squared with the shot noise when final detector performance specifications are developed.

This example is not an extreme one in any case. Requirements for the collection of one million electrons or thereabouts probably represents ultima Thule for the present.

It frequently happens, of course, that the number of electrons required for "resolution" based on the needed system S/N simply cannot be collected within the exposure time associated with a "strip mode" camera of the focal length required to support the experiment. This collection of sufficient signal is really the crux of the "physics" problem associated with low contrast image extraction. It is only compounded, of course, when light levels are lowered as is the case with an extended "photographic" day.

A means of circumventing this problem has been found in the application of time delay and integration (TDI) mode detectors. These detectors are area devices operated in a linear fashion. They operate as the electro-optical equivalent of an adjustable width exposure slit in a film type of photographic camera. As is shown schematically in Figure 2, the image scans the detector

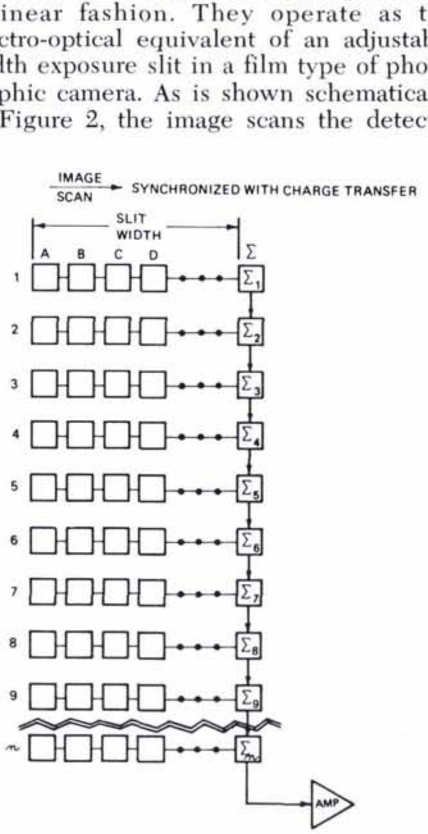

FIG. 2. TDI integrating linear array schematic.

moving, in this example, from left to right. As the image moves, the charges generated in the photosites are moved electrically in synchronism with the physical image motion. Thus, *all of the charge generated in photosites* A, B, C, etc., associated with one object point in the object space is eventually transferred to an accumulation site Σ_1. The row of such accumulation sites is then read out as a shift register *exactly in the same manner* as a single linear detector row might be.

The actual construction and operation of such a TDI detector is obviously not as uncomplicated as the above simplistic overview might imply. Since such detectors operate as sampled aperture systems, it is desirable to construct the summing photosites to operate in a multiphase manner, thus reducing the penalty to be paid in system MTF by effectively increasing the cut-off spatial frequency of the Sinc function associated with the charge (image) motion.

While the use of a TDI linear detector will provide the capability for collection of more signal, there are additional considerations which must be taken into account when such use is contemplated. First, it must be remembered that in extreme low contrast circumstances it is necessary to operate the detectors at a reasonable fraction of saturation. This being the case, some means of exposure control is needed. Since it is usually undesirable to reduce optical aperture (and thus diffraction resolution performance), the introduction of a variable number of TDI integrations *offers an attractive alternative to the* use of an iris diaphragm. An ancillary benefit derived from this approach is the minimization of exposure time with an attendant reduction of image smear.

Implied in the use of TDI detectors is the ability to subtract background (either D.C. alone or D.C. together with very low spatial frequency brightness variations) from the sensed scene. Collection of large numbers of signal electrons overcomes the problems associated with shot noise, but other problems remain. These are associated with variations in photosite responsivitity, and with dark current. These "signature" characteristics *must be quantifiable within the limits* needed to perform accurately the level of subtraction necessary to obtain useful low-contrast imagery. Since the signature for each variable number of TDI integrations may be different, it may also be necessary to quantify the required compensation for each such variable number of integrations. Such compensation is well within the state-of-the-art, but is made simpler and less costly when the variations inherent within the detector are minimized. It is therefore important that the requirements for dark current signature and responsivity signature be minimized in devices intended for high altitude low contrast remote sensing.

The photo-response of silicon based detectors generally fulfills the requirement that "good" responsivity be exhibited throughout the NASA "multispectral" wavelength domain (from 500 to 1100 nanometres). While less than ideal response can be obtained at the long wavelength extreme, such detectors generally perform as desired. Since, however, it can be anticipated that the need for more signal will always be with us, *it is important to note that* the responsivity of typical front-illuminated silicon charge coupled device (CCD) detectors can be enhanced though the application of "optical tailoring" techniques (Dyck and Wight, 1977). By carefully controlling the thicknesses of the several layers which comprise the detector structure, the optical transmission and reflection of the detector can be optimized. As is shown in Figure 3 (from Dyck and Wight, 1977), optimal optical tailoring can yield detectors with quantum efficiencies which average over 50 percent between 500 and 900 nanometres. While responsivity beyond 900 nanometres falls to just under 200 mA/watt at 1000 nanometres,

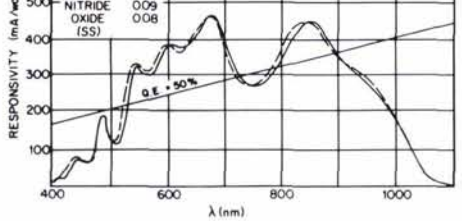

FIG. 3a. An optimized "optically tailored" design and its predicted spectral responsivity.

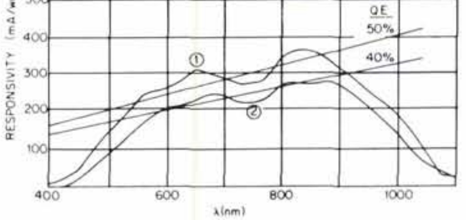

FIG. 3b. Measured spectral responsivity of an optimum and near optimum device structure.

the response obtained remains adequate for most remote sensing applications using this spectral band.

In addition to the specifics of signal accumulation, low noise amplification, and spectral response, simple physical factors may also impact the design and configuration of detectors specifically destined for use in remote sensing applications. For example, the usual "strip mode" linear electro-optical camera will utilize more than one detector "chip" in its focal plane. When this is the case, it is usually required that the several chips be effectively contiguous. Various optical-butting schemes have been used to accomplish this, most of which use some sort of beam-splitter or sharer (the latter being more conservative of light). For linear sensors which are only one "pixel" wide in the along-track direction, it does not matter whether a particular chip is being read out in the "left-hand" or "right-hand" way. When TDI detectors are used, however, the direction of image motion needs to be toward the final collective shift register. If a conventional beam-splitter is used, this implies that two versions of the detector chip will be needed. This difficulty can be circumvented by outfitting the detector with two readout amplifiers, one on each "end" of the chip. In this way the need for two mask sets is avoided.

It is possible to summarize the effects of high altitude low contrast imaging requirements on detectors and sensor design as follows:

- The sensor must be designed to incorporate the capacity for image processing in the removal of background and/or low spatial frequency variations in brightness.
- The sensor must be configured to include provisions for accurate signature compensation, both with regard to detector responsivity and dark current variations.
- The sensor must include balancing spectral compensation (as with filters) as required by the specifics of the subject experiment.
- The detector employed must be designed to provide the required responsivity, charge capacity, uniformity, and physical characteristics implied by the sensor design and signal collection requirements of the experiment.

TABLE 1. OBJECTIVE SPECIFICATIONS FOR CCD TDI CHIP

1. 1024 × 64 element array with integration steps at 1, 4, 8, 16, 32 and 64 integrations.
2. Q_{SAT}: 10^6 electrons.
3. Cell spacing 20 μM (20 μM × 20 μM pixel).
4. Horizontal output rate 1.5 MHz, vertical rate 1.5 KHz.
5. Dynamic Range: 3000 (0°C)
6. Temporal noise: (0°C, dark) 1.6 mV p-p max.
7. Responsivity: Similar to Fairchild CCD 131.
8. V_{SAT}: 1.2 V typical.
9. Photo Response Non-Uniformity (PRNU) ± 2% of sat (at 50%, O°C) 4 to 64 integrations; less 5 spikes (objective).
10. Avg. Dark Signal: 0.25% of sat (0°C).
11. Dark Signal Non-Uniformity (DSNU) requested ± 0.1% of sat. – objective only.
12. Bidirectional output register.

By way of example, it is pertinent to examine how the general types of requirements discussed here have influenced the design and development of a detector chip which is intended for application to the high altitude low contrast imaging problem.

The operational characteristics of the example detector, which is currently in the final stages of development at Fairchild, are summarized in Table 1. As a review of these features will show, this detector represents a great deal of progress toward fulfilling the requirements of high altitude low contrast imaging.

It is through the interplay of performance requirements (based upon system needs) and directed detector/sensor design that the future goals of remote sensing will be attained.

REFERENCES

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Dyck, R. H., and R. Wight, 1977. "A High Quantum Efficiency Front-Side Illuminated CCD Area Image Sensor," Proceedings SPIE, Vol. 116, Solid State Imaging Devices.