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User-Oriented Data Processing Considerations in Linear Array Applications*

Dark current, responsivity variations, and thermal drifts must be corrected.

Abstract: *Past generations of remote sensors on spacecraft have used mechanically scanned point detectors. To meet the requirements of flexibility, compactness, low power, and high reliability, future systems will make use of the solid-state line array technology. Line array applications provide the user with many advantages, such as increased dynamic range and geometric stability, but also present him with a unique set of processing requirements. Dark current, responsivity variations, and thermal drifts must be corrected for in thousands of individual elements.*

INTRODUCTION

Conventional point detector(s), i.e., mechanically scanned remote sensors, have provided useful visible information for the user-community for many years. With the advent of solid-state electronics, this conventional approach may be displaced by the placement of linear or area arrays of detectors in the focal plane of telescopic optical systems, thereby eliminating the scan mechanisms. This in itself is expected to improve continuity of data because of increased system reliability. Another difference in the solid-state linear array approach is that electronic scanning provides fully contiguous data in both along track and crosstrack directions as is not the case for bi-directional (crosstrack) mechanically scanned systems. For the latter, opto-mechanical corrections can be made to restore data contiguity. Again, this may add additional mechanical complexity. In addition, the character of the linear array focal plane is such that there is no change in the relative position of the detectors in the focal plane because they are spatially fixed and, thus, geometrically stable. Conversely, the mechanical scanner is required to very precisely maintain uniform scan dynamics and to make precision opto-mechanical measurements of scanner line-of-sight. Without delving into these technical differences, those who process the data are soon aware of how these differences affect their operations. In simplistic terms, the major difference in processing data from a linear array sensor is that the data are being derived from thousands of detectors, while in a mechanical scanning system, the data are derived from a single detector. Thus, one is trading the idiosyncrasies of a rather complex opto-mechanical dynamic assembly with a single detector for a static assembly containing thousands of detectors. Although the detectors are identical in physical terms, it is their non-identicality in electrical characteristics that clearly imposes unique data processing requirements on remote sensing

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systems using linear array technology. It is the purpose of this paper to introduce the users to the unique data processing aspects of linear array applications.

TYPICAL APPLICATION

Before discussing some unique aspects of linear array sensors, a brief introduction to the technology and how it is applied is in order. Figure 1 shows two photodiode, electronically scanned linear arrays arranged to form a contiguous array of 1024 detectors with 15 μm center-to-center spacing. In the example of Figure 2, four of these arrays are placed in the back focal region of a spectral separator containing prisms and dichroic filters. Off-track pointing is achieved with a pointable mirror. The resolution required of the sensor obviously dictates the quantity of detectors used in the focal plane.

DATA PROCESSING

Visible linear array technology has made rapid advancements in technical performance. As previously stated, the most significant aspect of the technology is that of processing information derived from possibly thousands of detectors with each detector having nearly identical characteristics. It is this minute difference in electrical characteristics that imposes a significant demand on data processing.

It is obvious that a ground facility can provide very sophisticated data processing by means of a large scale computer. With several calibration levels, equations can be computed to normalize the data, removing most nonlinearities and, thereby, providing very accurate relative radiometric data. The basic processing algorithm is shown in Figure 3.

For many users, a large computer facility is required. However, with this type of capability, it is likely that data turnaround time is lessened and the facility costs maximized. In this paper, we have chosen to place emphasis on what is referred to as real-time processing. In this sense, real-time processing means that as much processing as practicable is performed on board, thereby minimizing the complexity and cost of ground data processing.

Onboard processing in real time does not provide the sophistication of the ground system, but it does provide an effective means to simplify the ground collection and image recording. The application of calibration to the collected data is immediate because it was the last-obtained calibration data. This feature is of primary importance when related to thermal control, discussed in a later paragraph. There is no necessity to correlate the particular calibration sequence to the data.

The onboard processor still permits the use of the large ground processing facility where extreme accuracy is important. Several gray levels can be transmitted, and ground processing could provide the same results as is obtained without the real-time system.

Multilevel versus two-level calibration is of interest with real-time processing. Two levels—dark and one radiance level—are required to establish the basic dark and gain profile. After the two-level normalization, subsequent processing and transmission need not handle the larger signal dynamic range of data containing dark offset and gain errors. Onboard removal of gain and offset results in a reduction of several significant digital bits (a factor of four or more). Additional calibration levels will improve the data accuracy at the cost of a large increase in hardware. Each additional level would proportionately increase the hardware while the data improvement would not be recognizable to a simple

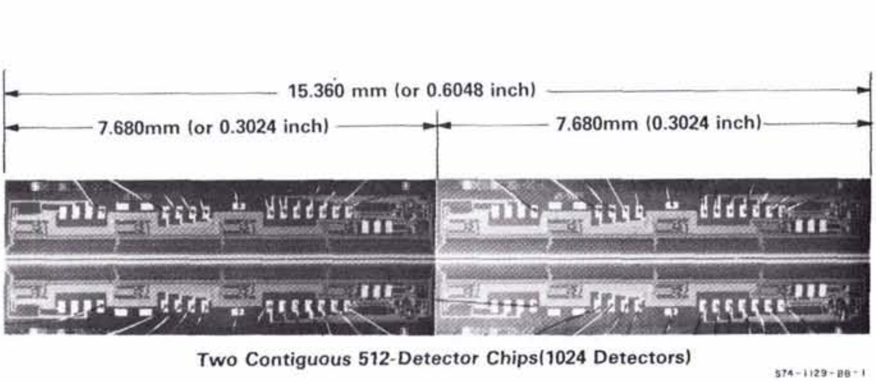

FIG. 1. Typical linear array.

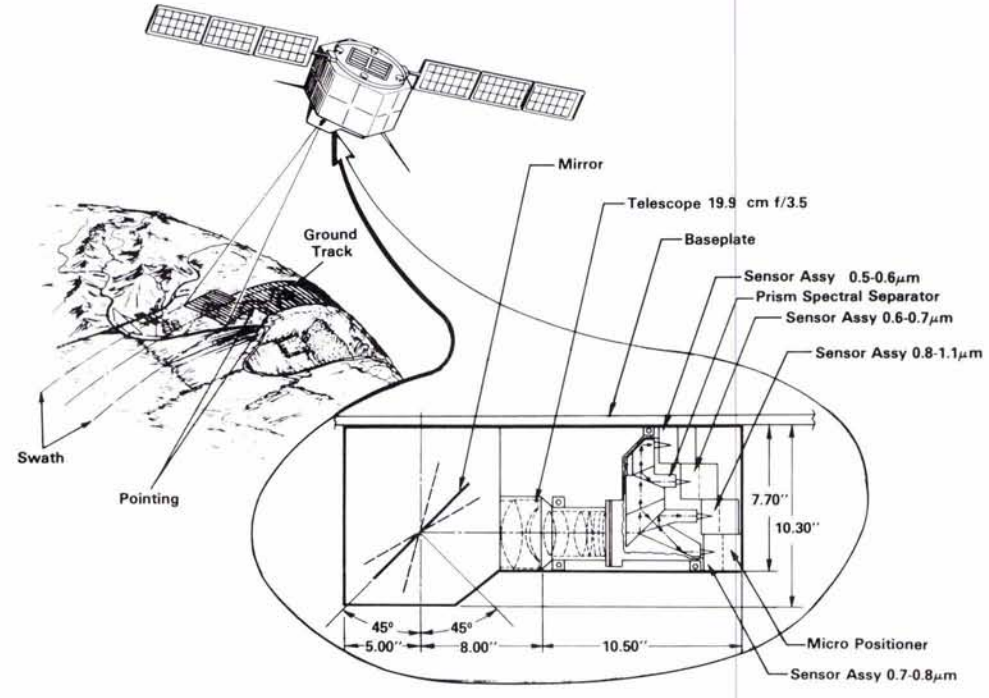

FIG. 2. Linear array sensor on a small spacecraft.

ground station. The maximum improvement would be to correct the 3 percent linearity which is compatible with a 32 gray level data range. Increasing the resolution to finer than 32 levels would not recognizably change the photographic reproduction and, therefore, would be of little value to users of primarily photographic imagery.

THERMAL EFFECTS

Thermal drift is of importance in photodetector arrays. Real-time processing provides a means of greatly reducing the thermal effects which, in turn, would ease the onboard thermal control of the photodetector arrays.

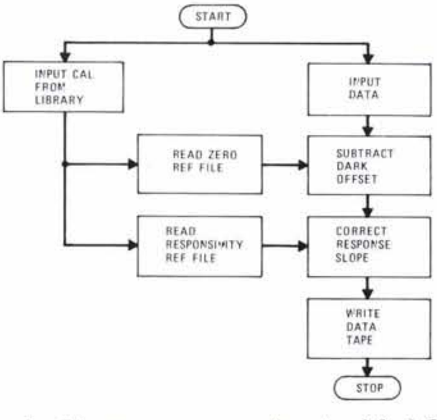

FIG. 3. Linear array processing simplified flow diagram.

The greatest thermal effect is the change of dark level. Consistent with dark current thermal variations in silicon, the dark offset changes approximately by a factor of two for each 10°C temperature change (see Figure 4). If we consider that the offsets between elements can vary up to 600 $\mu J/m^2$ equivalent input (i.e., a scene at the subsolar point using $f/4$ optics and $p = 0.2$) at 25°C, it can be seen that even a small temperature change causes a large signal error. The direct approach to minimize this error is to lower the temperature and precisely control it. Simplification of the thermal control system

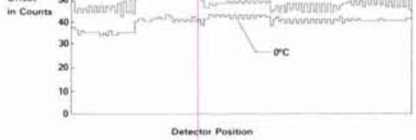

FIG. 4. Detector temperature dependence.

by widening the temperature tolerance can be achieved by real-time processing.

At 0°C, a ± 0.5°C thermal drift would cause a peak-to-peak error equivalent to 3.5 μJ/m^2 irradiance, or about 1 percent of the irradiance from a typical scan at the subsolar point. For a system design requiring the drift error to be held below the general noise level, it would be necessary either to control the 0°C baseline temperature to within ± 0.1°C or else to lower the baseline to −30°C controlled to ± 0.5°C, with a resultant error of 1 μJ/m^2. A system with real-time processing could allow a 0.2°C/min drift rate about the nominal 0°C baseline, while maintaining the 1 μJ/m^2 maximum error, by performing a dark reference at 30 sec intervals. The shutter mechanism causes some data loss (possibly a few milliseconds), and at least three scans are necessary to ensure a good reference. Therefore, for a data loss of less than 0.1 percent (i.e., 200 m loss out of 200 km ground track at 900 km orbit altitude), tight thermal control can be avoided.

NOISE

The imaging system with real-time processing has several noise-related characteristics. Random noise creates errors in the offset and gain factors as they are read into memory, causing errors in the gray levels. A coherent gray level error is created during the normalization process. The results and possible solutions of the error sources are discussed in the following paragraphs.

Noise is always present and is contributed by both the detector (see Figure 5) and the data processor. This noise is low level and random, and, in high radiance scenes, it does not itself significantly degrade an image. The RMS noise level of experimental systems has been shown to be less than 1 percent of the maximum irradiance. A greater problem is the effect of noise on the real-time processor. A candidate mechanization uses a single scan line for each calibration level. On the basis of that line, the real-time processor removes offset or applies a multiplication factor. Noise on that line, therefore, becomes a coherent error in the data, which creates streaks in the processed image.

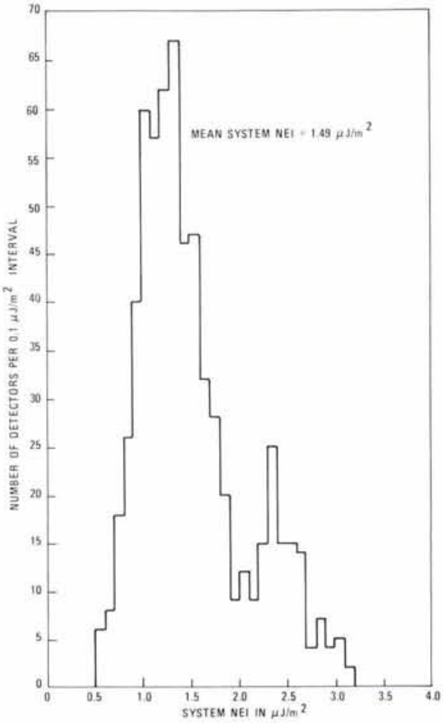

FIG. 5. Typical noise histogram.

CALIBRATION

A calibration means is required for any remote sensor from which accurate radiometric data is required. The nonuniformity of gain, linearity, and dark level between individual photoelements of an array increases the necessity for calibration. Of importance in this discussion is the understanding that, unlike most point detection systems, an array cannot and (with proper system design) need not calibrate on every line. Inclusion of a real-time processor does not change the necessity or the technique of calibration of the solid state array. What is accomplished by the use of the real-time processing is the increased flexibility of calibration.

For onboard dark reference calibration, it is necessary for the remote sensor instrument to block the aperture by using a shutter for a dark level reference; also to provide a source of illumination such as a solar input or tungsten bulb as a gain reference. These inputs are scanned, thus providing the data for either ground or real-time processing. The difference occurs in the timeliness and sophistication of the calibration data usage.

In summary, calibration techniques are the same for real-time or ground processing. In addition, real-time processing does not limit the ability to include calibration levels for higher quality ground processing. Real-time onboard processing permits the implementation of simplified ground processing and display.

Real-Time (Onboard) Processing

Real-time digital processing (see Figure 6) includes removing element-to-element offset, normalizing the element-to-element gain variations, compensating for the spatial offset caused by the staggered layout of the detectors in the array, and the incorporation of a two-calibration point algorithm (dark and half scale).

For linear arrays with a staggered layout of elements, it is required that outputs from half the elements be delayed in order to produce a contiguous image. The delay is achieved by using delay lines inserted into the system between the A/D converter and the bus multiplexer. While the undelayed buses are input directly to the multiplexer, the buses to be displayed are input to shift registers.

Offset correction is the process of subtracting the dark output of each cell from its operating output. An eight-bit subtractor performs the arithmetic operation using operating data from the multiplexer and offset data stored in memory. The offset correction system is calibrated by covering the array to exclude any illumination and forcing the subtrahend of the subtractor to zero. One scan of data (minus zero) is then stored in the offset memory. On subsequent lines the data stored in the offset memory is input to the subtrahend of the subtractor in synchronism with the operating data at the minuend. Thus, the subtractor output is the operating data with the offset removed.

Gain correction is the process of normalizing the gain variations of the detectors. Once the offset has been removed, the transfer function for the cells is approximately linear, so that a single multiplicative factor can be used. To calibrate the system, the array is illuminated with one-half of the maximum scene irradiance. A data point with the offset removed is stored in the gain memory.

For each element, because the offset of up to one-half of the dynamic range is removed, the half of maximum irradiance will produce a maximal digital output that is 25 percent of the uncorrected maximum output for the highest gain element. Therefore, a minimum overall system gain of two is required in the real-time processor to make full use of the dynamic range of the digital system. An element with the lowest gain correctable by the real-time processor will produce a digital output of only eight counts with the same input irradiance.

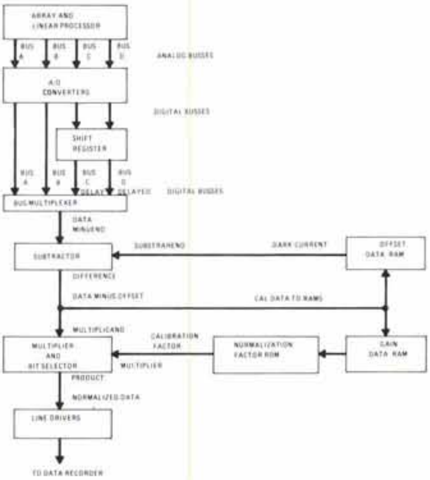

Fig. 6. Real-Time processor block diagram.

The memory data are used on a cell-by-cell basis for two purposes. First, it addresses the calibration factor to select an appropriate multiplicative factor. Second, it controls the bit selector to select eight of the 16 bits output by the multiplier. This second function is equivalent to division and thus serves to extend the range of the multiplicative factors available. The data at this point are corrected for off-set, gain variations, and staggered array geometry.

Conclusion

Laboratory experimentation has shown that images generated using real-time processing will be of high quality. The advantage of this technique is that there is a significant reduction in ground data processing complexity. The disadvantage is that additional electronics complexity is required in potential spacecraft sensor applications. For further applications, the tradeoff between simplified ground data processing and more complex onboard processing must be given careful attention.