COMPUTER-AIDED ANALYSIS OF CCD LINEAR IMAGE SENSORS

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ABSTRACT

This paper describes special test equipment and techniques to collect and process image information from charge coupled devices (CCDs) by digital computer. The video channel was traced from the CCD to the direct memory access bus of the Interdata Computer. Software was developed to evaluate and characterize a CCD for (1) dark signal vs temperature relationship, (2) calculation of temporal noise magnitude and noise shape for each pixel, (3) spatial noise into the video chain due to dark signal, (4) response vs illumination relationship (gamma), (5) response vs wavelength of illumination (spectral), (6) optimization of forcing functions, and (7) evaluation of an image viewed by a CCD. The basic software differences and specific examples of each program operating on real data are presented.

I. INTRODUCTION

The rapid growth of CCD technology presents a need to develop special test equipment for the timely measurement of critical CCD characteristics. These characteristics, such as dark signal and photoresponse, vary from lot to lot and device to device within a lot that is dependent on material purity, uniformity, and process control. Thus, a rapid evaluation system is required to expedite the screening of selected pieces from low yield processes to be used in an assembly and to assure a high probability of system success.

Perkin-Elmer's Optical Technology Division has responded to this need by developing Low Light Level (LLL) applications for CCDs; the CCD arrays are to be used as star trackers and fine guidance sensors. For these applications, the greatest uncertainty is in the selection and performance of the focal plane sensors. To determine and reduce this uncertainty, we have initiated a program to evaluate candidate sensors for the specific applications. Our computer experiments were conducted on Fairchild's CCDs 121. (Refer to Section III and see Fig. 1.)

Fig. 1. Perkin-Elmer's Reliability Engineering Laboratory at OTD for CCD evaluation

The conditions of the applications were simulated with test equipment (thermoelectric cooler/vacuum chamber, translation table, etc.) so that the evaluation would be biased to the application requirements. Various light sources were used: a 2850°K, HeNe laser and monochromatic light from 400 - 1100 nm; color correcting filters were also used which resulted in a simulated 5000°K source.

The tests were configured to evaluate and characterize the CCD for the following phenomena:

- The effect on the output by varying the input electrical forcing functions.
- The functional dependence of dark signal to the temperature of operation.
- The spatial variations of the dark signal signature.
- The magnitude and shape of the temporal variation of each photoelement's (pixel) output.
- The linearity of photoresponse as a function of illumination level (gamma).
- The absolute photoresponse as a function of input light source wavelength (spectral response).

Data was recorded in initial tests by oscilloscope photographs which were capable of recording all pixels for each integration period, yet lacked the resolution of any individual pixel, precise measurement of magnitude, or information about the temporal noise magnitude. It was apparent from these photographs that the variations from pixel to pixel were greater than those budgeted for the system application. Dark signal subtraction was required to eliminate the "signature" of the array. Further, calibration was necessary to eliminate the "odd-even" output effect and nonuniformity of pixel responsivity. In addition, we had to quantify the temporal noise to assure the operation of the system in a favorable signal-to-noise ratio.

The measurement system must be capable of collecting data from the device under test at data rates up to 500K bytes per second. This data rate is necessary to allow the recording of every pixel for an integration period. The system must store data from multiple integration periods so that statistical averaging can be performed. Data from many different experiments must also be stored so that variations from experiment to experiment can be evaluated -- i.e., dark signal vs temperature at 9 temperatures, photoresponse vs illumination level at 11 illumination levels, and photoresponse vs wavelength at 29 wavelengths.

The number of tests, the detail of the measurements, and the required speed dictated the requirement for a computer to collect, store, and reduce the voluminous data. Once the need for the computer was established as the data recording system, this permitted additional features to be considered. Simulation of specific applications was now possible. The ability to translate images and point sources by the array and record the output from the entire image was feasible. In addition, software was developed to simulate several algorithms of data compression that would be performed in the equipment of the final system configurations.

II. TEST EQUIPMENT

1. Drive Electronics

The applications for which this special equipment was designed required the use of multiple CCD line arrays operating with a common integration time and sequential readout. The electronics was designed to allow readouts from 1 to 16 arrays per integration period. The integration period could be altered by adjusting a master clock; all other required clocks track this master clock. All input clocks and voltage levels were adjustable so that the performance of the chip under test could be optimized.

The electronics timed the injection of the charge into the test points on the test array so that charge transfer efficiency (CTE) could be measured in the analog shift registers. This method of measurement eliminated the inherent difficulty of light spot alignment and focus for measurements from a single illuminated pixel, or the nonuniformity of photoresponse that interferes with the CTE measured by uniform illumination.

2. Thermoelectric Cooler/Vacuum Chamber Assembly

The device under test was mounted on a beryllium pedestal which, in turn, was mounted on a thermoelectric cooler. The cooler allowed the chip to be operated at temperatures as low as -40°C. The array clock drivers and first preamplifier were inside a vacuum chamber which could be either pumped down for vacuum operation or backfilled with dry nitrogen for atmospheric pressure tests.

The thermoelectric cooler/vacuum chamber assembly was mounted on a precision, three-axis translation table. (The X and Y directions have remotely controlled stepper motors that provide positional control in two tenths of micron steps. The Z-axis is manually controlled and used for focus.) This apparatus was used to perform simulated image motion on the detectors.

3. Video System

The signal output and the compensation output were subtracted in a low noise preamplifier inside the vacuum chamber. The signal was sent to two sample-and-hold amplifiers. One sample-and-hold amplifier sampled the waveform reference level just ahead of the video information; the other sampled the video output. The reference was then subtracted from the video in the next amplifier. This operation provided DC restoration to the signal and rejected time-correlated noise. Next in the video chain was an optional gain of ten amplifier. For low signal levels, it was necessary to increase the resolution of the following analog-to-digital converter (ADC) circuitry.

Two ADC's were available. Both have 8 bits and 1 MHz conversion time. One has 5 volts full scale; the other, 10V full scale and, combined with the optional times ten amplifier, yields full scale ranges of 0.5V, 1.V, 5.V and 10V. Timing of the conversion occurred after the video sample-and-hold had become stable. The eight data bits and the end of convert pulse were sent to buffer/drivers for transmission to the computer.

4. Computer

An Interdata 7/32 Minicomputer was selected to collect and process the video data from the CCD under test. A Universal Logic Interface (ULI) board was employed to aid data transfer. Note that the addition of line receivers and a flip-flop integrated circuit (to govern the "handshake" control) to the ULI makes the test bench look like just any other high speed peripheral to the computer. This arrangement transfers data at rates in excess of 2 megabytes per second. The computer, containing two 5 megabyte disks (one removable) and two tape drives for bulk storage, services two hardcopy and two video graphics terminals.

III. COMPUTER EXPERIMENTS

We are engaged in the performance evaluation and characterization of Fairchild CCDs 121, both the X and Y configuration. The test equipment described in Section II allowed flexibility in the configuration of specific tests. The tests of primary importance were highlighted in the Introduction of this paper.

1. Optimization of Parameters

The first operation was for the optimization of the electrical forcing functions (the manufacturer's device data sheet was the reference). The primary adjustments were to the "Photogate" voltage and the "Output Gate" voltage. These had the greatest impact on the "odd-even" effect. Fig. 2 illustrates this effect and the computer output most helpful in observing it. Fig. 3 is the same data as received by the computer and displayed in oscilloscope fashion. By iterating the adjustments, the effect could be eliminated. After the optimization procedure had been completed, all the parameters were entered and stored into the computer.

2. Dark Signal vs Temperature

The variation of dark signal vs temperature is a critical parameter for system applications since it provides an indication of device quality. Classical physics predicts the generation of electron hole pairs to diminish by approximately a factor of two for every 8°C reduction in temperature. This relationship does not hold at temperatures close to 0°C and lower. It is postulated that the variation from the theory is due to various trapping states. The lower bandgap and the lower density of these states make their effect noticeable only at lower temperatures. The density of the traps gives a quantitative measure of the quality of the device under test.

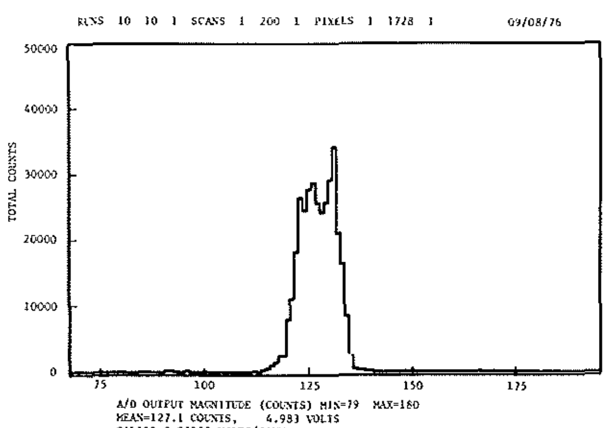

Fig. 2. Frequency distribution showing "odd-even" effect

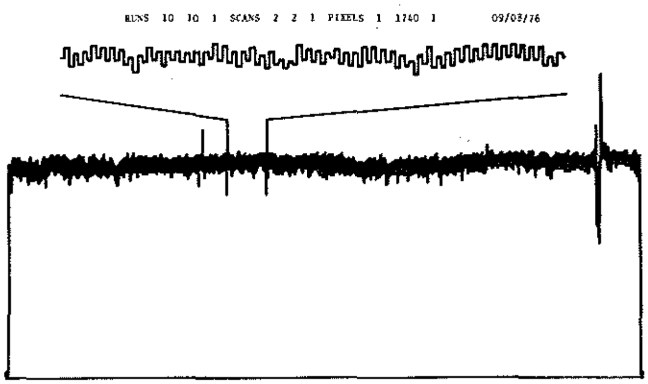

Fig. 3. Raw data in oscilloscope fashion showing "odd-even" effect

The first test that was performed on an array was for dark signal as a function of temperature. The test data was recorded by the computer at nine temperatures between -35°C to 10°C. A typical computer generated output is shown in Fig. 4. A theoretical model with provisions for both classical and trapping effects was drawn on the same figure.

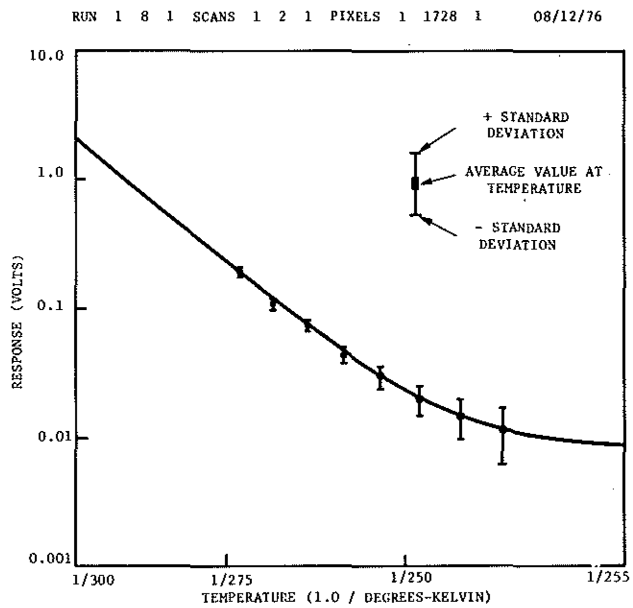

Fig. 4. Dark signal vs temperature functional relationship

3. Temporal Noise

The signal-to-noise ratio available for signal processing is a function of all the gains and added noise of each electronic stage in the video chain (Fig. 5). It has been proven that the most appreciable noise source is the device on the chip output amplifier.

Data collected for the dark signal vs temperature test consisted of 500 samples of each of the 1728 pixels of the array at each of the nine temperatures. The computer can use this data to calculate the shape, magnitude, and location of a three parameter Weibull distribution for each pixel (Figs. 6 and 7). A "composite" pixel was also calculated from the average of the 1728 shape, location, and scale parameters. This knowledge allowed determination of a threshold value for the video signal that will effectively reduce false hits while maximizing detection (Fig. 8).

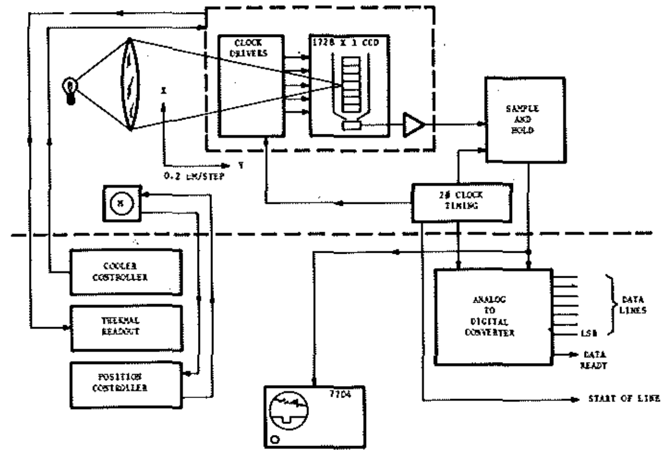

Fig. 5. CCD video chain to interdata computer

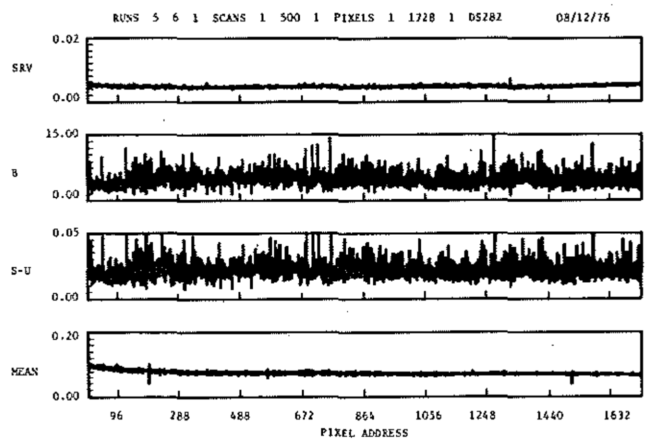

Fig. 6. Plots of three parameter Weibull values vs pixel number

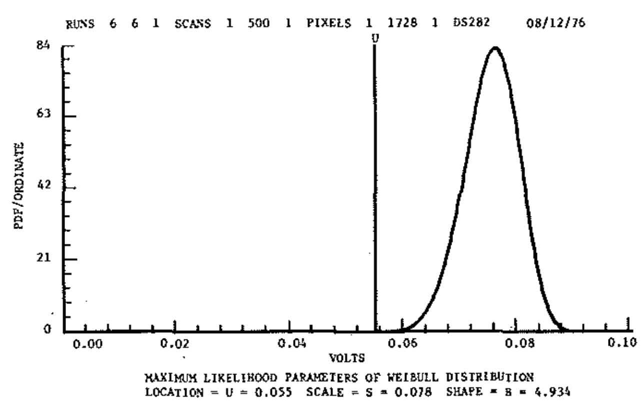

Fig. 7. Composite Weibull distribution of all pixels

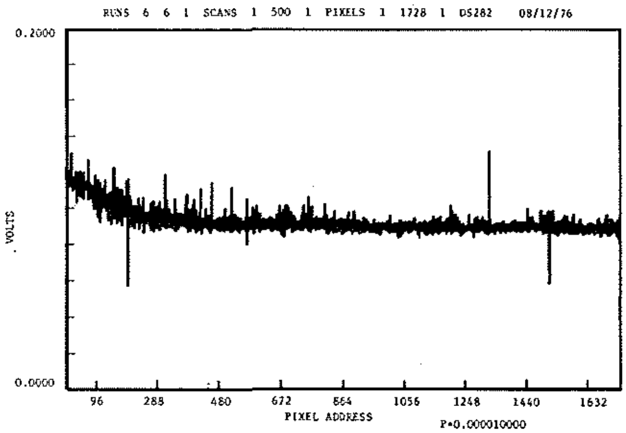

Fig. 8. Threshold voltage required for each pixel to assure a probability of false hits of 10^{-5}

4. Spectral Response

The response to light of different wavelengths is of prime importance to any detector application. The arrays tested exhibited response from 400 nm to 1100 nm. The method of the test involved the use of two monochrometers: one covered the range from 400 to 800 nm; the other, from 700 to 1100 nm; both in 25 nm steps. The overlapping points from 700 to 800 nm were used as a check for accuracy.

The computer collected dark signal data from the array and then data at 17 different wavelengths, using the visible region monochrometer. This was followed by another dark signal for reference and the monochrometer was changed. The procedure was repeated for the infrared region monochrometer.

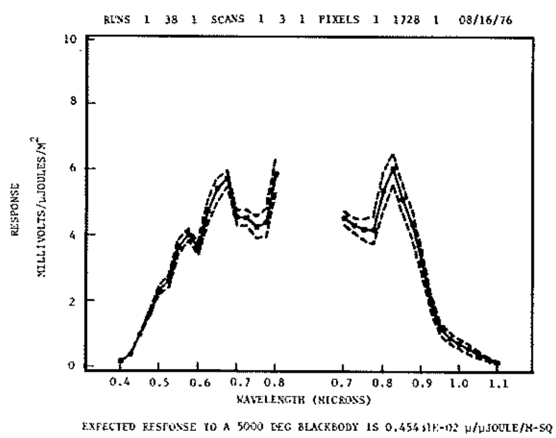

Fig. 9. Spectral response from the two monochrometers used

Fig. 9 shows the data from the two monochrometers and the standard deviation about the average. Fig. 10 folds the two together. The theoretical response to a light from a 5000°K full radiator was also calculated. The spectral response of any pixel or group of pixels could be calculated, and variations from end to end could be easily mounted (Figs. 11 and 12).

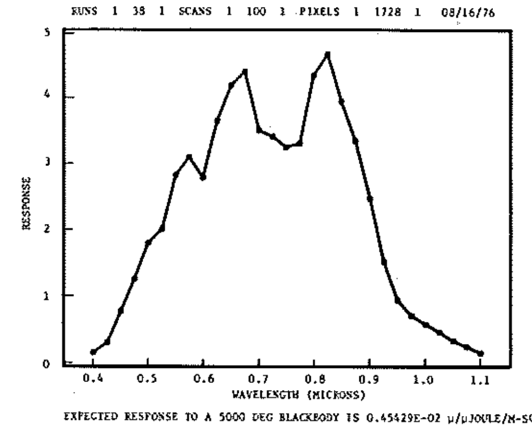

Fig. 10. Spectral response of all pixels averaged

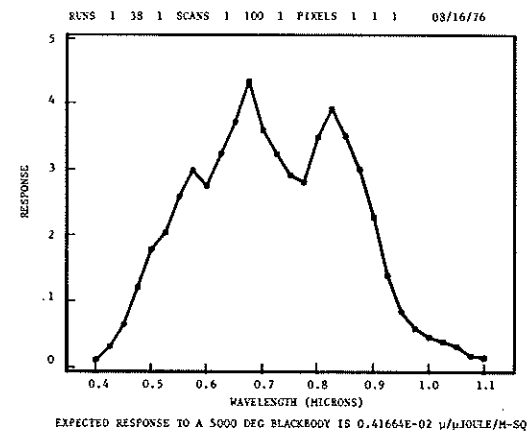

Fig. 11. Spectral response of pixel number one

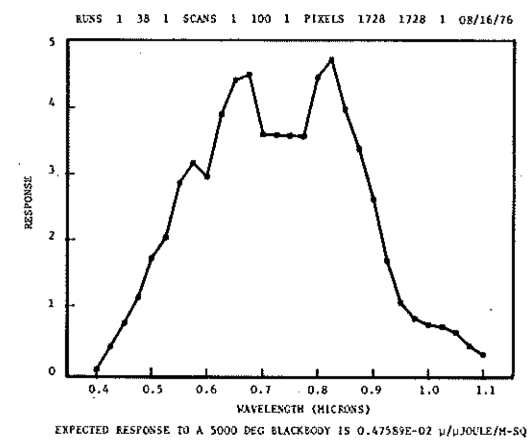

Fig. 12. Spectral response of pixel number 1728

5. Photoresponsivity and Linearity of Response (Gamma)

Particular interest has been placed on the linearity of response to different illumination levels. Film and television tubes both have an exponential response to light intensity. The theory for semiconductors predicts the exponent of Equation (1) to be 1.0.

$$\frac{\text{Illumination No. 1}}{\text{Illumination No. 2}} = \left(\frac{\text{Volts Response No. 1}}{\text{Volts Response No. 2}}\right)^{\gamma} \quad (1)$$

To evaluate this effect, the device was exposed to illuminations ranging from 2.μ j/square meter to 2600μ j/square meter (5000°K source, 80 msec integration time), and the data was collected by the computer. A dark signal reference level was collected before and after the complete range of illuminations; this approach ensured that the temperature of the array had not changed during the test. The dark signal data was also used for pixel-by-pixel subtraction of the dark signal before photoresponsivity calculations were made. A typical output (Fig. 13) produced the voltage output vs illumination level on log-log axes and the least-square-best-fit to the equation:

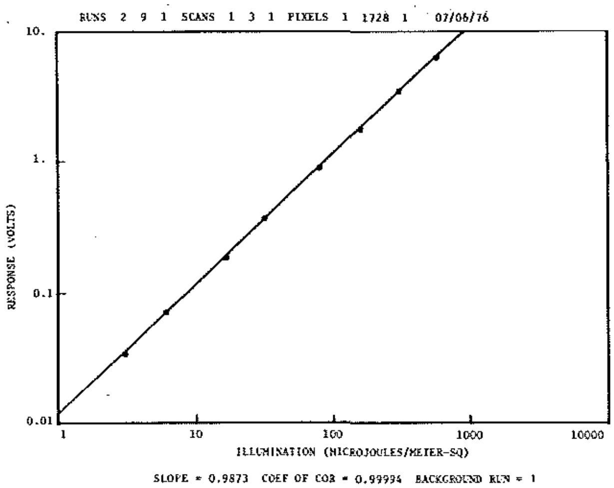

Fig. 13. Log response vs log irradiance curve

$$\log(Vi - DS) = \log B + \gamma \log(Hi) \quad (2)$$

where

Hi = the illumination of the ith level

Vi = voltage output at the ith level

DS = dark signal at test temperature

B = responsivity at 1μ j/m^2

γ = linearity exponent gamma

This test can be done for any pixel or group of pixels.

A measure of the charge transfer efficiency of a device could be made using the data available from the photoresponsivity and linearity test. It can be shown that:

$$\eta = \sqrt[M]{\frac{V_{N+2} - DS_{N+2}}{V_N - DS_N}}$$

where

η = charge transfer efficiency

M = number of transfers

N = last real pixel number

V_N = voltage from the last pixel

DS_N = dark signal from the last pixel

V_{N+2} = voltage two clock pulses after the last pixel

DS_{N+2} = dark signal two clock pulses after the last pixel

6. Image Analysis

The driving force behind the characterization of an imaging array was to be able to remove from the output signal spatial effects of the sensor and leave only effects of the image. The remaining temporal effects were the sole limitation on the devices with respect to LLL performance.

Operational differences between imaging and characterization were immediately apparent. The most obvious was that characterization tests must precede imaging. Second, for characterization, the image scene had to remain constant. The effect of temporal noise could then be used to smooth the transfer function of the ADC (multiple samples may be averaged together to obtain values between the assigned ADC codes). Imagers have a changing scene from integration period to integration period; they cannot time average the signal, and so were limited by the temporal noise and the ADC's least significant bit (LSB). One should be cautioned about using relative calculations below ADC code 5, as the error could be in excess of 10% of the assigned value with no temporal noise, and greater if noise is present. The probability of the value assigned by the ADC being less than ±1/2 LSB is a function of the code width to the standard deviation of the noise ratio (Fig. 14).

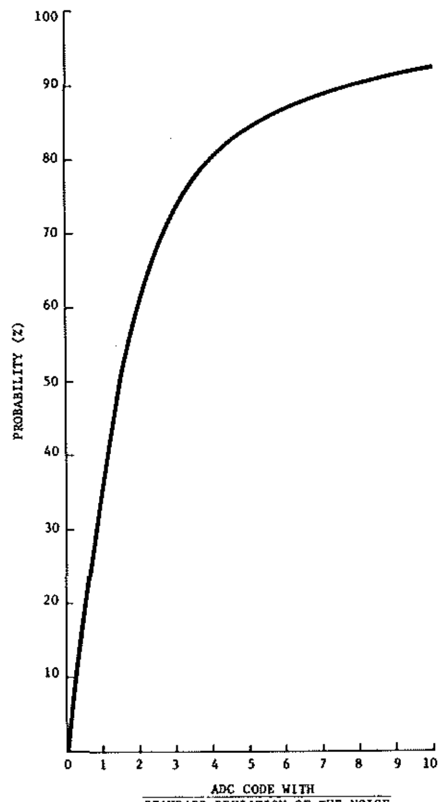

Fig. 14. Probability that the value the computer assigns to the signal is within ±1/2 least significant bit

There is no advantage in an imaging application to have the width to sigma ratio less than 1.5. This is the point at which the probability of an error greater than ±1/2 LSB equals 0.5. Lower ratios will favor the output not to be in the nearest conversion level to the signal.

In the simulation of our application, a spot generator was used to create a 20 μm diameter spot (5000°K blackbody). The X-axis stepper table was moved in two tenths of μm steps, 6.5 μm per integration time. The data could be plotted on the display screen. The options allowed for pixel-to-pixel dark signal subtraction, thresholding, and zoom magnification in any combination. Fig. 15 presents the results of thresholding alone. The required threshold dropped dramatically (for a 10 and 0.0049V RMS noise, 3 bit is sufficient) after background subtraction (Fig. 16). The centroid noted was the calculated prediction of the time and location of the spot's transit.

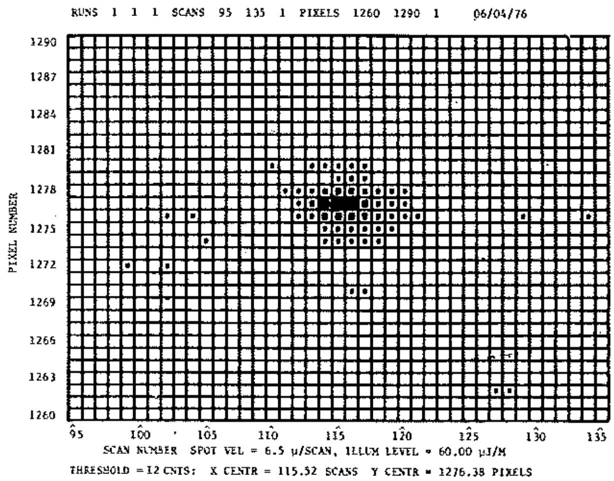

Fig. 15. Simulation star transiting array threshold of 12, no background subtraction

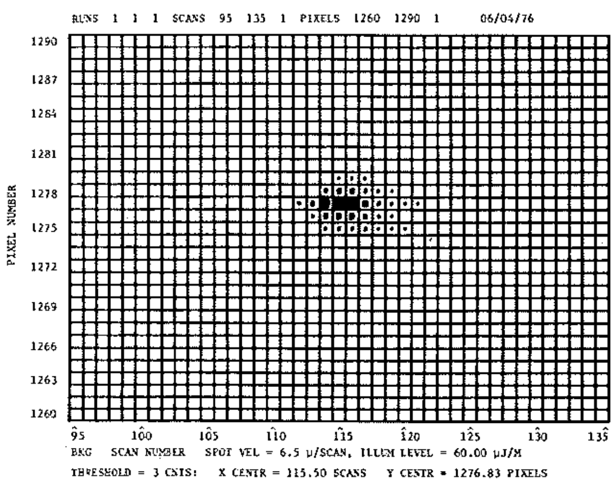

Fig. 16. Simulation of star transiting array threshold of 3, background subtracted

IV. RESULTS AND CONCLUSIONS

The computer is necessary for the comprehensive characterization and evaluation of CCDs. Not only does it measure and store the output of each pixel for each integration period, but its speed allows the collection of multiple array readouts during real time -- i.e., for our system, 500 successive samples in 40 seconds in which the array generated the information. It is the short time duration which maintains the integrity of the experiment. The temperature, clocking voltages, light sources, etc., cannot vary appreciably during the length of the experiment. The new data may be operated on immediately for verification purposes and/or stored on magnetic tape as a data base for multi-experiment comparisons or for future evaluations.

This software package is unique, extensive, and expanding. More than just data recording is provided. The data is reduced and fit to physical models such as:

- Dark signal vs temperature:

$$V_{DS} = A + BT^{3/2} e^{-EG/2KT} + CT^{3/2} e^{-EM/2KT}$$

- Photo response:

$$\log (V_{ILL} - V_{DS}) = \log B + \gamma \log (Hi)$$

The basic data is extended to make predictions:

- The probability of a false bit given a particular threshold voltage.
- The threshold voltage required to assure a particular probability of a false bit.
- The expected responsivity to any color temperature blackbody.

Application hardware and operation can be simulated in software to determine the most effective design algorithms for a particular system. Our system is not constrained to a particular device type. Three different video amplifiers in two different vacuum/thermo-electric cooler enclosures have been employed for both line and area arrays. The video chain can be broken at any point before the ADC, and other electronics can be substituted as necessary.

The overall results of testing (Table 1) reveal the dark signal for the Y configuration devices to be about 10μ j/m^2; photoresponse: 54μ V/μ J/m^2; temporal noise equivalent signal: 0.9μ j/m^2; and saturation exposure in excess of 600μ j/m^2.

By comparison, the X-configuration devices (which have an extra amplifier stage on the chip) exhibit 16 μj/m^2 equivalent dark signal; 227μ V/ μj/m^2 photoresponsivity; 1.1 μj/m^2 noise equivalent signal; and saturation in excess of 2600 μj/m^2. They demonstrate dynamic ranges of 600 and 2000, respectively, for the Y and X types.

Table 1. CCD test results

S/N	Dark signal at -10°C	(mv/ μj/m^2) Responsivity	Noise
285040 Y	0.1008v 9.8μj	11.2 220 gain	
285044 Y	0.1158 11.μj	13.49 220 gain	
285054 Y	0.08068 6.6μj	12.2 220 gain	
285055 Y	0.0452v 2.8μj	16.1 220 gain	
226263 X	0.08337 16μj	5.32 20 gain	
256282 X	0.07545 16μj	4.54 20 gain	4.9mv 1.07μj
276347 X	0.04096 9μj	4.53 20 gain	5.37mv 1.18μj