Performance Evaluation of CCD Imagers

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Introduction

The Naval Electronics Systems Command recently supported a program to develop CCD photosensor imaging arrays under a contract with Fairchild Camera and Instrument Corporation. The development effort resulted in two versions of CCD imagers, a 190(H) x 244(V) element array and a 380(H) x 488(V) element array utilizing interline transfer, buried channel technology. Two camera systems were fabricated to demonstrate sensor performance. This report details tests which were performed on these systems at the Naval Air Development Center in Warminster, Pennsylvania.

Test Conditions

A collimator was used to generate test imagery. A collimator is essentially a high quality lens with an illuminated transparency located at the focal distance of the lens. Thus, a camera system's lens looking into the collimator sees an image at infinity.

Test patterns were illuminated with a 2854K tungsten source operated without an infrared blocking filter. Light level variations were made with aperture type filters to permit use of the camera lens at a single aperture and to avoid color temperature changes. Wavelength dependent tests were made with a high intensity incandescent source and narrow band color filters. No corrections were made for lens performance.

Light value calibrations were made with a Spectra-Pritchard Model 1980 photometer for 2854K measurements and with a Molectron PR200 radiometer for the wavelength dependent measurements. Photographs were made from a CONRAC Model RQA 17-inch TV monitor, on Polaroid type 57 film. A more detailed discussion of evaluation techniques for solid state imagers may be found in reference 1, where the measurement problems peculiar to the CCD and CID structures are described.

Sensitivity

Using a 100% contrast USAF resolution slide in the collimator, monitor photographs were taken with the sensor surface illumination varied from 1.4×10^{-1} down to 1.7×10^{-5} fc (foot-candles). These tests were made with the 380 x 488 camera, and with the sensor array maintained at 0° C. As light level was reduced, amplifier gain was increased as required to maintain a constant video output (equal to the 80% saturation value at high light level) or until no usable improvement was obtained (low light level, fixed pattern disturbance limit reached). Controls were also available for adjustment of clock voltages on the sensor. The horizontal readout clock controls were initially optimized for maximum signal amplitude (display contrast) at each light level. The results obtained are illustrated in figure 1. Note that the lowest light level for perception of the image is limited primarily by the fixed pattern interference, not by random electrical noise.

A more practical adjustment of the clock controls is a single setting for all light levels. Here, the clock adjustments were set for the best compromise between good resolution and minimum fixed pattern interference over the entire range of light levels. The result, illustrated in figure 2, was improved resolution and a more limited low light range as compared to figure 1.

Note in both illustrations that the dynamic range for quite usable picture information extends over a 75:1 ratio. The difference in resolution noted probably indicates that the increased sensitivity of figure 1 was due to incomplete charge transfer. For a 30% contrast pictorial target (a "real world" scene), minimum discernable pictures were limited to a higher light level. This is illustrated in figures 3 and 4.

Limiting Resolution

At the same time that the photographs of figures 1 and 2 were taken, a close visual inspection of the monitor screen was made to obtain readings of limiting resolution. Figure 5 illustrates the measurements made with a white background (black bars) slide. Note that the element size in both of the arrays is 0.030(H) x 0.018(V) mm, resulting in Nyquist points of 16.7 and 27.7 line pairs per millimeter, respectively. For the 8.8 mm vertical size of the 380 x 488 array, this corresponds to values of 294 and 488 TV lines per picture height, respectively.

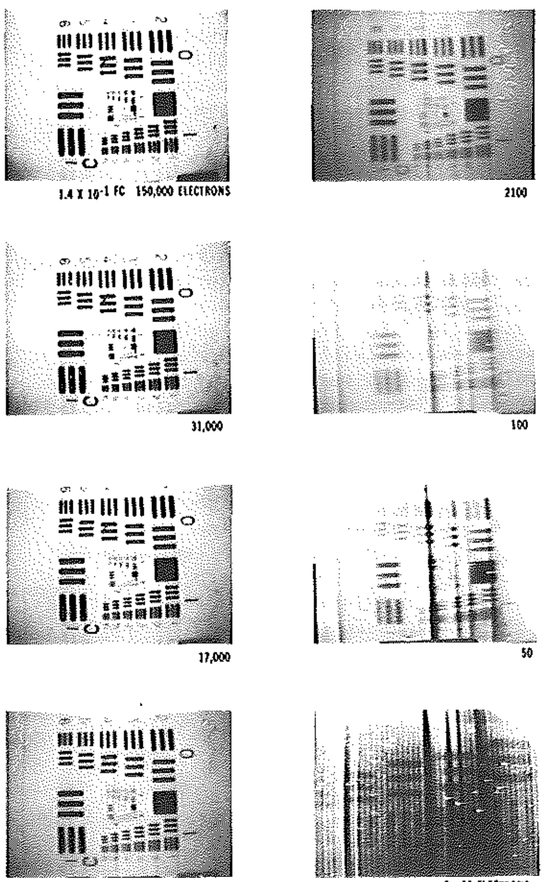


FIGURE 1 - USAF Test Pattern (100% Contrast) H Clocks Set for Maximum Contrast at Each Level

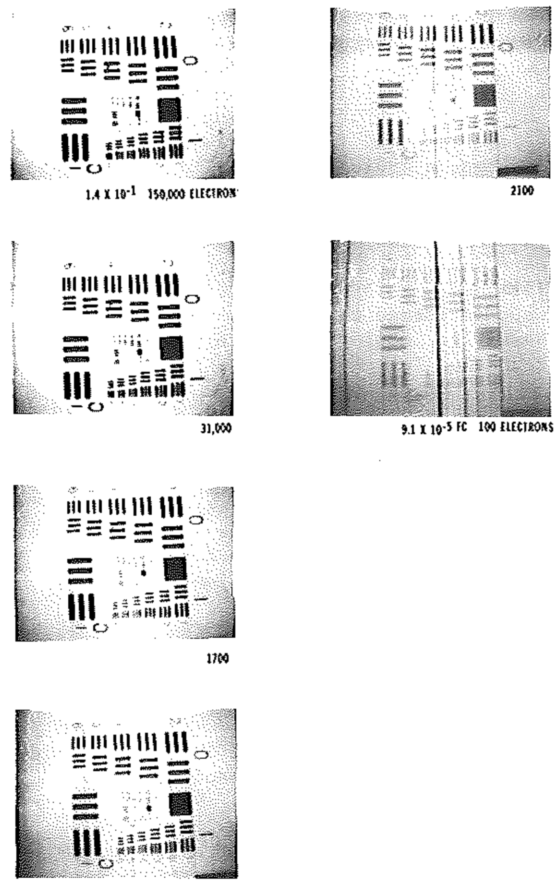


FIGURE 2 - USAF Test Pattern (100% Contrast) Normal H Clock Adjustments

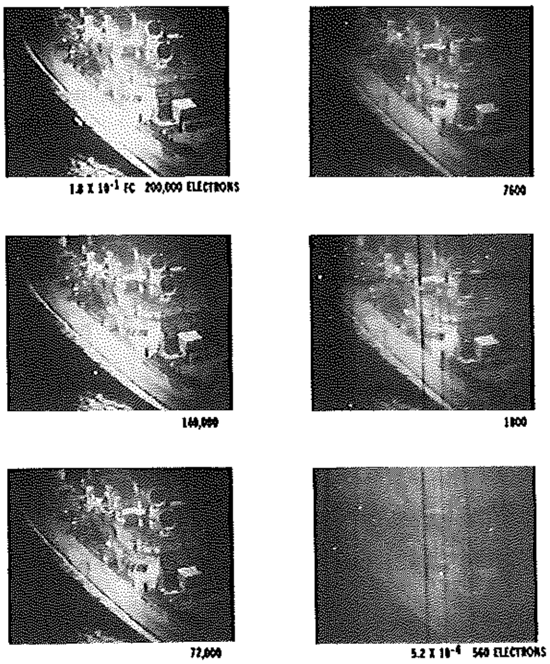


FIGURE 3 - Ship Scene (30% Contrast)

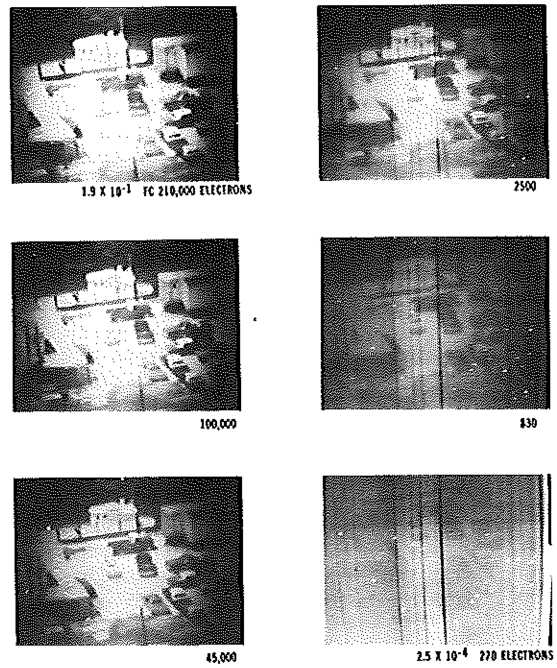


FIGURE 4 - Dock Scene (29% Contrast)

As shown in the photographs of figures 1 and 2, pattern information may only be seen, at low light levels, in small areas amid large fixed pattern and shading disturbances. Measurements were therefore made by moving the test pattern until bars just at the limit of resolution were located in such an optimum area.

Additional data points, obtained with low contrast slides, were plotted in figure 6 to show the effect of contrast variation upon resolution. Note that limiting resolution does not fall until contrast is below 20%.

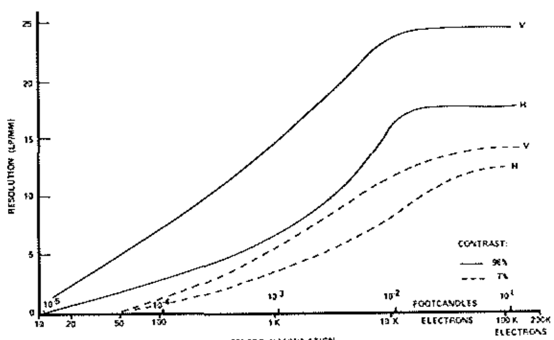


FIGURE 5 - Resolution Versus Light Level

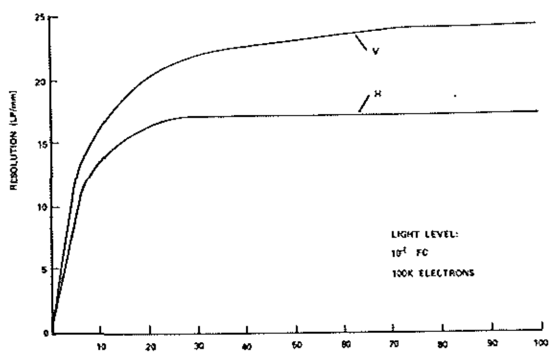


FIGURE 6 - Resolution Versus Contrast

Square Wave Response

Video sampling for response and signal-to-noise ratio measurements utilized a CVI (Colorado Video, Inc.) Model 321 video analyzer. This unit samples a given point on a line in each video field (or frame) and holds that value until the next field (or frame). The sampling point can be located anywhere in the picture area. The output of the analyzer represents a high frequency waveform converted into a low frequency signal which may be recorded on an X-Y chart recorder. Accurate waveform and amplitude measurements are possible since a very long filter time constant may be applied in the recording process.

For the square wave response measurements noted in this report, the sample point was fixed at the center of the picture area. Thus the signal amplitude was independent of any illumination shading. The image of a SAYCE pattern (100% contrast, frequency sweep bars) was optically moved across the sampling point by means of a translatable slide carriage. Measurement of signal amplitude versus spatial frequency were taken from an X-Y recording of the sampled CVI output.

Figure 7 shows the effect of white light level variation on square wave response. Figure 8 shows the wavelength dependent performance. Focus was optimized for each wavelength.

For light levels near saturation, horizontal square wave response was measured to be 65% at the Nyquist point of 16.7 lp/mm. Figure 8 shows that square wave response was lowest at long wavelengths. This was also observed as an increase in apparent sharpness of a pictorial subject with the application of an infrared cut-off filter, as is illustrated in figure 9.

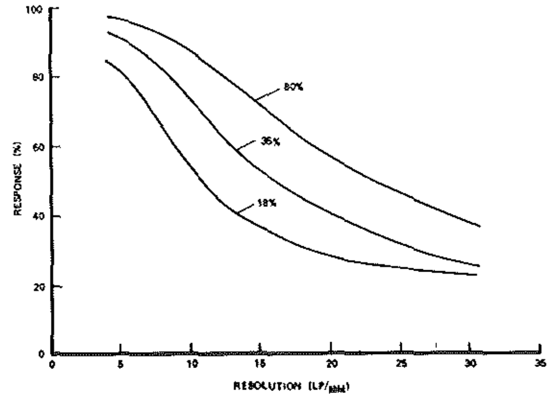


FIGURE 7 - Square Wave Response Versus Light Level (% of Saturation)

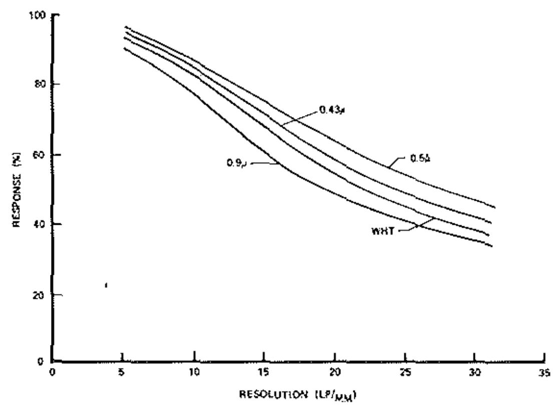
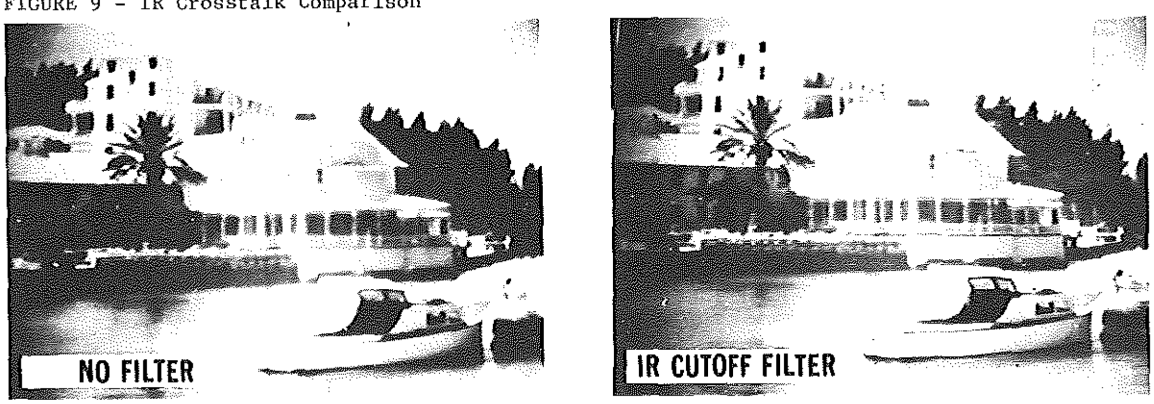


FIGURE 8 - Square Wave Response Versus Wavelength

FIGURE 9 - IR Crosstalk Comparison



Signal-to-Noise Ratio

For SNR (Signal-to-Noise Ratio) measurements, the sampled output of the CVI unit was processed in an Intronics R301 RMS module to derive the AC noise component over a long averaging period.

Using a simple low frequency bar pattern, readings of white and black signal amplitudes were taken while at the same time the noise level in the white area was measured. The difference between white and black amplitudes, divided by the rms noise level in the white area, is defined as the SNR. The test results are shown in figure 10. The highest light value represents a point just below saturation.

The reproduced image was remarkably free of the familiar random noise effect even down to the light level where picture information was obscured by fixed pattern disturbances (below 10^{-3} fc). At 10^{-2} fc the SNR was 60 (36 dB).

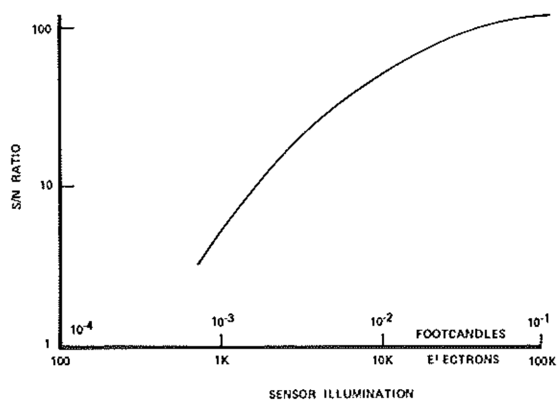


FIGURE 10 - Signal to Noise Ratio Versus Light Level

Image Spreading

Image spreading was measured by placing a very small light source in a long focal length collimator. This provided a spot of light approximately the size of a single CCD element, on the sensor surface. Neutral density filters were used to control the intensity.

The photographs in figure 11 illustrate the results. The light intensity for the "normal" condition was adjusted to be just below saturation. Note that there are two white spots visible in the center area of the picture. The upper left one is the light spot while the lower right one is a defect in the sensor. Subsequent photographs in the sequence illustrate the light spot image spreading as the light spot intensity was increased.

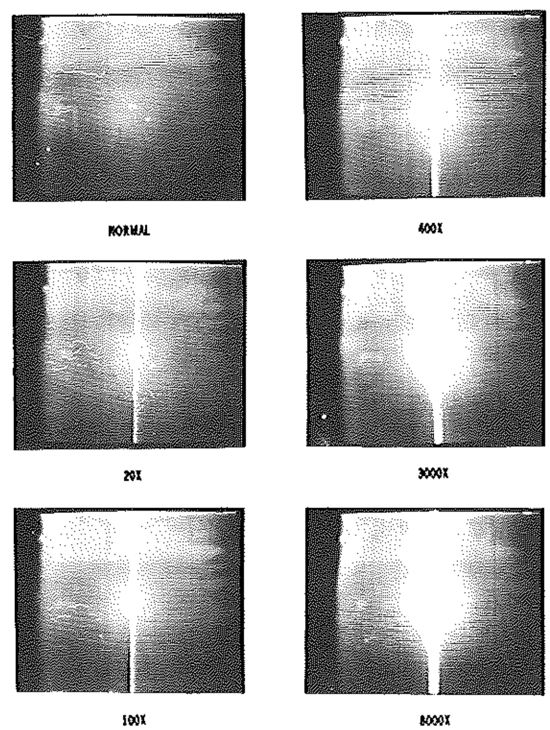


FIGURE 11 - Image Spreading

A qualitative measure of the spreading was made by recording the output of the CVI line sweep sampling function on the X-Y recorder. At a 20:1 light overload a spread of the displayed spot to three elements and the appearance of a two element wide saturated vertical line was noted. At an extreme (8000:1) overload, the resulting display spot was 26 elements wide with 6 columns saturated.

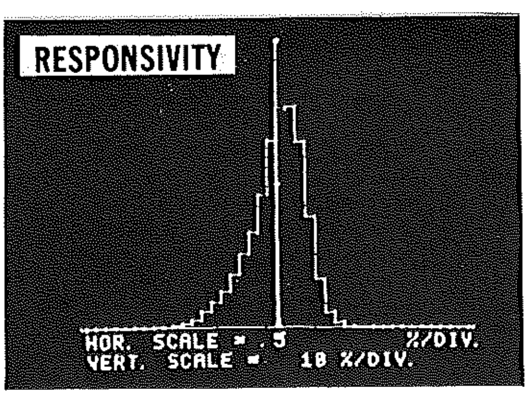
Uniformity

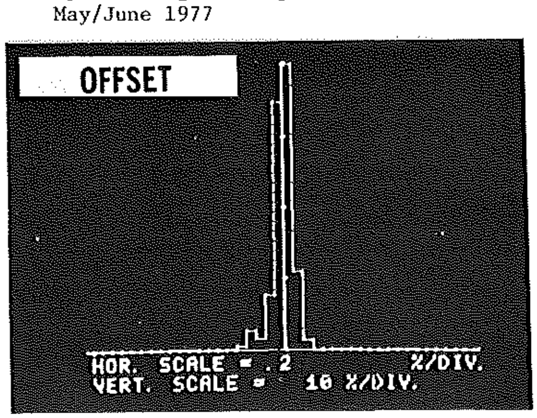
The degree of variation of responsivity and offset level was assessed using a 128 x 128 element subarray central to the 380 x 488 element sensor. A Biomations Model 8100 transient recorder under control of a Varian Model 72 minicomputer was used to sample voltage levels at each of 128 contiguous pixels or 128 contiguous lines of video. The process was done once with the array uniformly illuminated near the saturation level, and once in complete darkness.

The data from each of the two 128 x 128 element scans is stored on a disc memory and later processed by the minicomputer. The responsivity signature is obtained by subtracting the matrix sampled in darkness from the matrix sampled at full illumination, and normalizing to an estimate of the mean saturation level. The offset matrix is the normalized version of the "dark" matrix.

The normalized responsivity and offset data was then sorted to derive the histograms presented in figure 12. Note that the bin widths are 0.5% for responsivity and 0.2% for offset. The standard deviation was found to be 1.4% for offset. 99% of all samples fell within 4% of the mean responsivity and 0.8% of the mean offset.

FIGURE 12 - Histograms





Conclusion

To sum up, excellent performance was demonstrated in many test parameters. Square Wave response measured 65% at the Nyquist point (294 TVL), SNR was 60 at 10^{-2} fc (36 dB), and limiting resolution was almost constant down to 20% contrast.

Imagery at a high light level was remarkably free of spot and column blemishes. However, the arrays tested did not produce a usable overall image at very low light levels, because of the severe fixed pattern and shading disturbances which appeared. Although performance readings were taken over a 10,000:1 range (1.9×10^{-1} to 2×10^{-5} fc) on the sensor, a more practical range was a 75:1 range (1.5×10^{-1} to 2×10^{-3} fc).

The low light level performance values, therefore, must be considered as an indication of possible performance if the "cosmetic" defects can be controlled in future production.

A follow-up contract is currently underway for design refinements to improve manufacturability and to include hermetic sealing and built-in provisions for cooling the 380 x 488 array. Also, under the same contract, there is a program to define and fabricate a series of camera system modules which will support and demonstrate both area and line array CCD sensors in a variety of applications.

References

1. S.B. Campana, "Techniques for Evaluating Charge Coupled Imagers," Optical Engineering, 16:3:267, May/June 1977