CHARGE COUPLED DEVICES FOR LOW LIGHT LEVEL IMAGING

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ABSTRACT

The results of tests conducted on CCD (Charge-Coupled Device) imagers are presented. The tests include signal transfer, dark current, amplitude response, noise, blooming, limiting resolution, and dynamic range. The performance of CCD's at low light levels is predicted for various noise conditions. The predictions are compared to the measured performance of conventional vacuum camera tubes. The goals of the continuing CCD development program are discussed.

INTRODUCTION

The Naval Electronics Systems Command is sponsoring development of CCD's (Charge Coupled Devices) in a three-phase, 30-month program. During Phase I, three manufacturers - Fairchild, RCA and TI (Texas Instruments) - were funded to develop and deliver 12 500x1 line imagers and 12 100x100 area imagers. Upon completion of Phase I, devices were tested at the respective manufacturer's facilities. Some of these tests were witnessed by a review team, made up of representatives from three Navy laboratories - Naval Air Development Center, Naval Electronics Laboratory Center and Naval Research Laboratory. The deliverable items were then divided among these laboratories and during March 1973 further testing was performed. In April 1973, as a result of the performance demonstrated, Fairchild Camera and Instrument Corporation was selected to continue the Navy's CCD development program. This paper will present some of the test results that led to that decision. In addition, the applicability of present and future generations of CCD's to low light level imaging is discussed.

TEST RESULTS

SPATIAL RESPONSE

The CCD technologies employed by the three Phase I contractors can be divided into two classes: surface channel technology, where charge is transferred along the interface between the insulator and semiconductor; and buried channel technology, where a potential minimum is created in the semiconductor away from the interface. In the former, employed by RCA and TI, a charge bias or "Fat Zero" is required to inactivate the surface states at the interface, which would otherwise result in poor CTE (charge transfer efficiency). The potential minimum in buried channel devices serves to confine charge in a plane away from the interface, thus avoiding surface states and the necessity of providing Fat Zero.

Fairchild's three-phase 500 element line arrays have consistently demonstrated a CTE higher than 99.99% when clocked at 300 kHz without Fat Zero. When clocked at 1 MHz, the output registers of Fairchild's two-phase 100x100 element area arrays have also demonstrated CTE's higher than 99.99%. Fairchild has also reported 10 MHz operation of 64 element arrays demonstrating a CTE greater than 99.9%.

RCA's three-phase, 500 element line arrays have demonstrated an average CTE of 99.8% when operated at frequencies as high as 8 MHz with a bias charge of about 20% of the saturation level. RCA's three-phase, 128x160 area arrays demonstrate an average CTE of 99.1% at 5 MHz with Fat Zero levels ranging from 20 to 40% of saturation.

TI's four-phase, 500 element line arrays have demonstrated a CTE of 99.65% at 10 MHz with 15% Fat Zero. Their three phase 75x100 element area arrays have exhibited a CTE of 99.93% at 100 kHz, 15% Fat Zero.

The results of the square wave amplitude response measurements are presented in Fig. 1. The measurements were made in the centers of the arrays, with the bar patterns perpendicular to the direction of high speed readout, phased to produce maximum modulation. Because of its low CTE, the RCA array showed a drastic reduction of amplitude when the pattern was positioned at the end of the array furthest from the output. Even at the "good" end, all of the arrays exhibited amplitude response degradation indicative of losses other than those due to lateral transfer. These effects may be due to optical and electrical spreading.

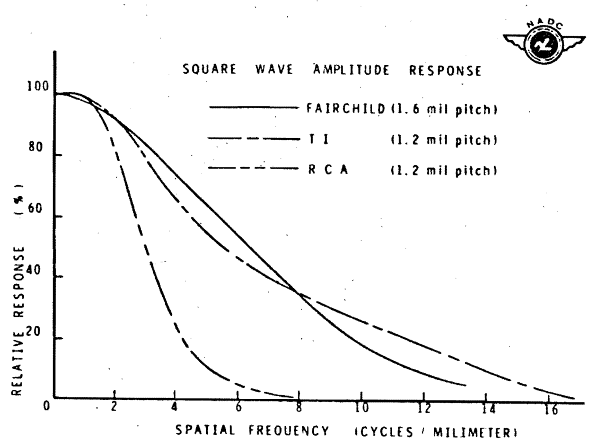


FIGURE 1
SQUARE WAVE RESPONSE

Since all of the arrays were several mils thick and illuminated from the same side as the transfer electrodes, one could expect image degradation due to the diffusion of charge produced in the substrate back to the transfer plane. In particular, near infrared radiation penetrates deeper into the substrate than does blue light, thus more charge spreading might be expected. To assess the magnitude of this effect, a Fairchild area array was used to image a Limansky test chart (see Ref. (1)) over a range of spectral conditions. Some of the resultant imagery is reproduced in Fig. 2. The group of bars just to the right of the wide, white bar results from an input pattern of alternating white and black bars of equal width. The bar width at the CCD image plane was 2 mils, or 1.25 times the center-to-center spacing of the elements along a horizontal line. The next burst of four white bars is half the width of the first burst, thus beyond the Nyquist sampling limit.

Under each of the four spectral conditions illustrated in Fig. 2, the first group of bars can be clearly resolved. No perceptible modulation change occurs as the spectrum is changed from broadband (2854°K) to monocromatic, near infrared radiation (1.06 μ). Thus, it appears that front illumination of thick arrays results in no extreme resolution loss.

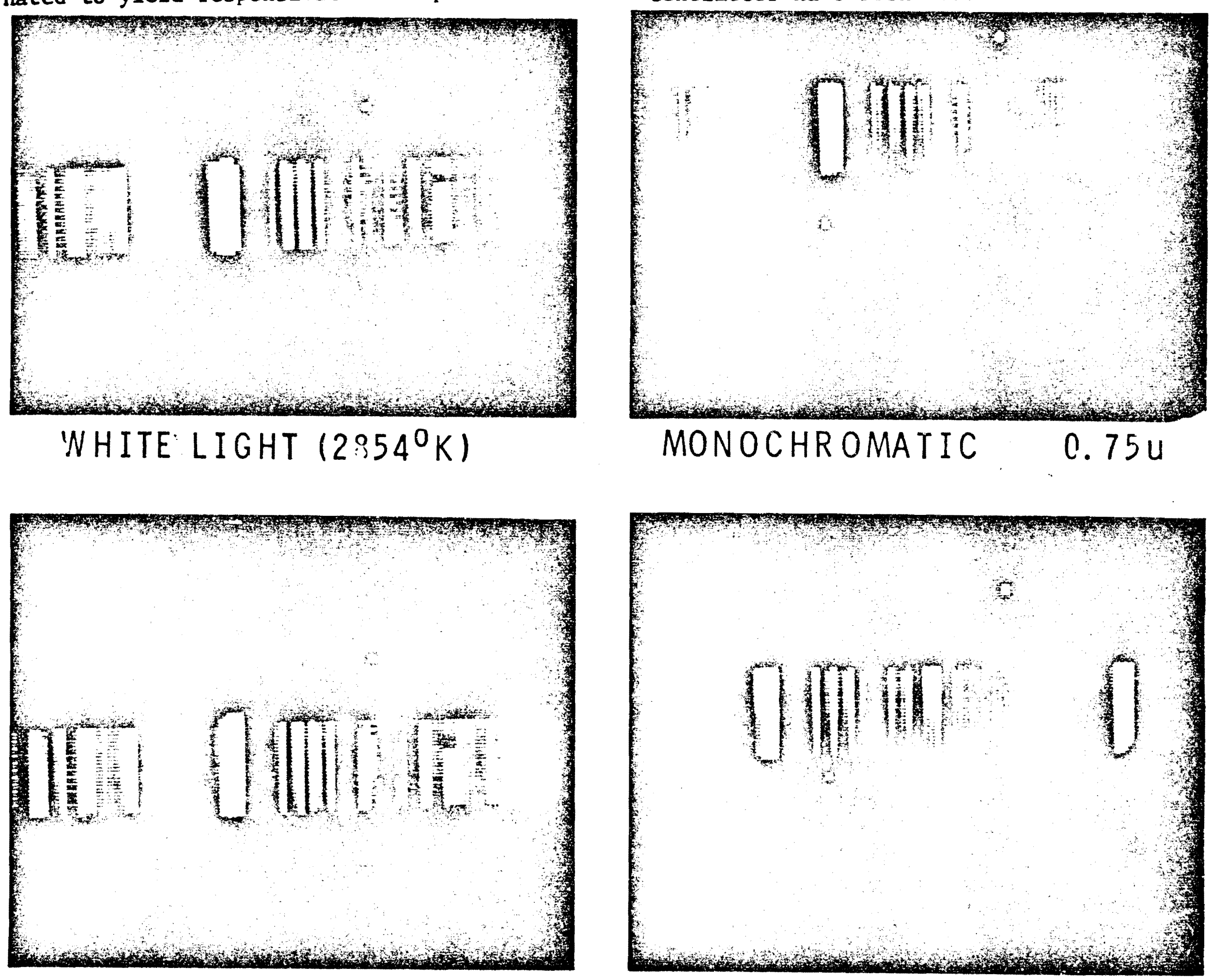
SIGNAL TRANSFER

The delivered arrays were tested to determine their responsivity to white light (2854°K). All of the arrays were illuminated from the electrode side. The resultant signal current was divided by the total radiant power (integrated over the entire blackbody spectrum) incident on the image area, including the area occluded by transfer gates. The highest responsivity was exhibited by Fairchild line arrays, where numbers as high as 50 milliamps per watt were recorded. Fairchild area arrays employ an interleaved transfer organization which requires that about 54% of the active area be occluded to shield the transfer registers. Also, an additional layer of polysilicon refractory gates is required in the area array. Thus, the responsivity of the area array was measured to be only 20 ma/w.

Both RCA and TI area arrays utilize a vertical frame transfer structure, where the storage area is not included in the image area. Thus, these arrays are not subject to the loss that is inherent in the interleaved transfer structure. However, arrays produced to date must be illuminated through aluminum transfer gate "fingers" and therefore lose considerable responsivity. The responsivity of RCA's array was measured to be 30 ma/w, while TI's array demonstrated 18 ma/w. Theoretically, vertical frame transfer devices can be thinned and back illuminated to yield responsivities comparable to silicon vidicons. However, the thinning and mounting of a CCD is a major processing step which has not been demonstrated to date.

Spectral responsivity of a Fairchild line array has been measured, and is presented in Fig. 3. The numerous peaks and valleys in the response are attributed to interference in polysilicon and oxide layers.

The lowest dark current density has been demonstrated by Fairchild line arrays. Densities as low as 2 nanoamps per square centimeter have been measured. Area



WHITE LIGHT (2854°K) MONOCHROMATIC 0.75u

MONOCHROMATIC 0.9u MONOCHROMATIC 1.06u

MULTISPECTRAL IMAGING WITH FAIRCHILD CCAID100

FIGURE 2

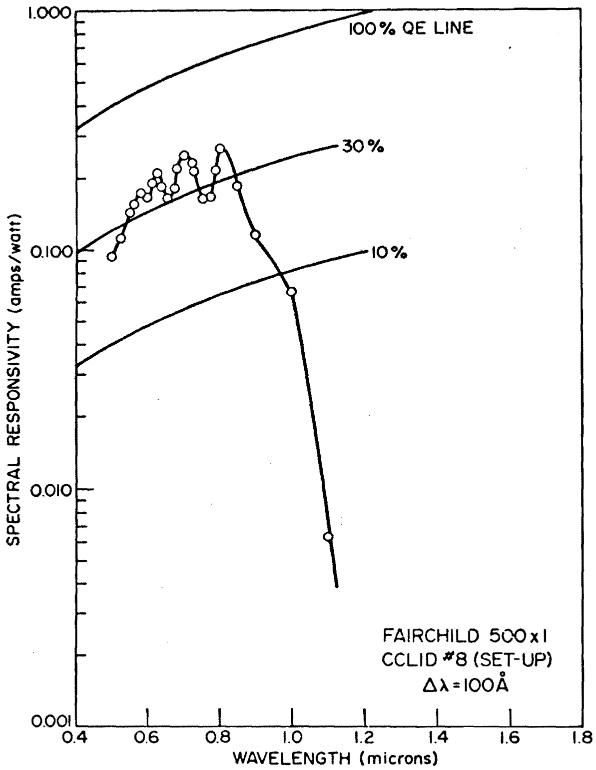


FIGURE 3
SPECTRAL RESPONSIVITY

arrays have not been as good. The best leakage current densities measured on area arrays from all three suppliers have been in the range from 10 to 15 na/cm^2 The worst area arrays exhibited dark current densities as high as 200 na/cm^2.

Fairchild line and area arrays typically saturate with 1.5 million electrons per element per frame. However, beyond about 0.5 million electrons, the potential minimum is cancelled, and the device operates in a surface channel mode. RCA's line arrays have demonstrated a full well capacity of 5 million electrons, while their area arrays saturate at about 0.3 million electrons. Full well capacity of a TI area array was measured to be 2.5 million electrons.

NOISE

In Fig. 4, noise measurements of a TI area array are presented, as a function of signal electrons. The measurement was made by sampling the voltage level of a single picture element once each frame. The standard deviation of a large sample set was then calculated in terms of an equivalent signal, expressed in electrons per well per frame. With the array in darkness, the measured noise equaled the signal produced by about 700 electrons per well per frame. With increased illumination the noise increased, maintaining a level approximately twice that of the expected shot noise. These measurements were performed at TI's facility during the on-site testing phase. Verification of this data has not been done.

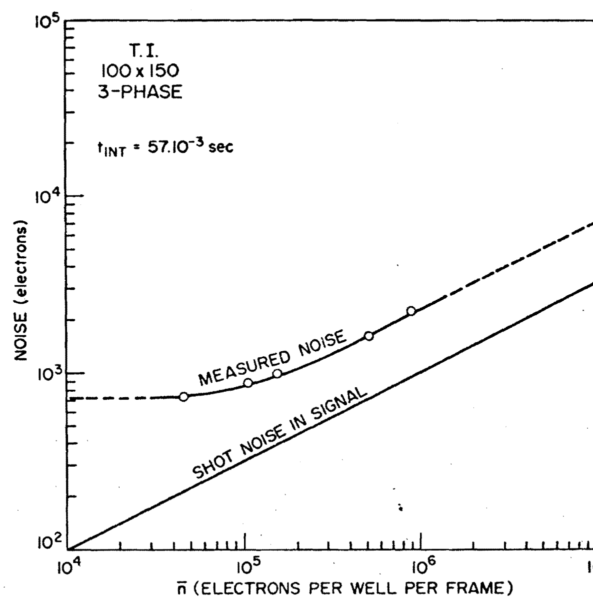


FIGURE 4
TI NOISE MEASUREMENTS

Extensive noise testing of Fairchild line arrays was done at the Naval Air Development Center. In Fig. 5, the NEP (Noise Equivalent Power) is plotted versus total incident power for a 500 element line array operated at 300 kHz. The minimum rms noise level is measured to be equivalent to a 250 electron signal. Following the noise analysis of Carnes and Kosonocky[2], this level may be attributed to the uncertainty of resetting the 0.3 picofarad floating diffusion (~220 electrons), and to the background charge generation noise (~120 electrons).

In Fig. 6, the data from Fig. 5 is replotted in terms of the electron variance as a function of signal charge population. Also plotted in Fig. 6 are the theoretical reset and photoelectron noise components. The measured data appears to approach these asymptotes at each extreme. However, the data taken at charge levels beyond 0.3 million electrons indicates a third component of noise, the onset of which is rather abrupt between 200,000 and 500,000 electrons. The difference between the data and the sum of the two theoretically determined components has been plotted as a fourth curve on Fig. 6. One possible explanation for this discrepancy is surface state noise, since the discrepancy becomes significant at a level corresponding approximately to the point where the buried channel becomes saturated and the device shifts into a surface channel mode. However, the slope of the "fitted" analytical curve indicates a square law dependence between the noise variance and signal level, above 0.3 million electrons. This fails to agree with the fast interface state noise model hypothesized by Carnes and Kosonocky[2], which does not identify a signal dependent term. The origin of the discrepancy is therefore presently unresolved.

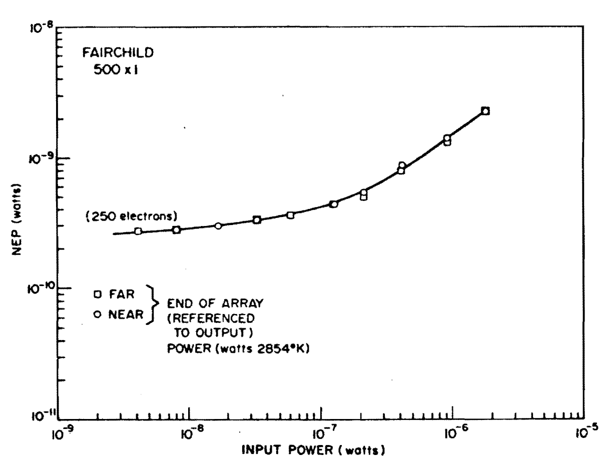


FIGURE 5
NOISE EQUIVALENT POWER

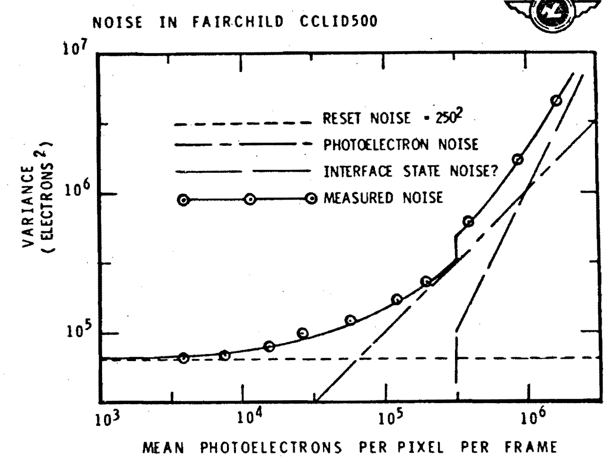
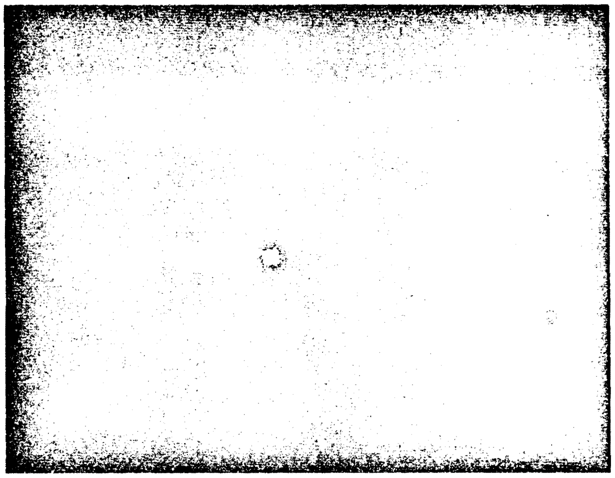


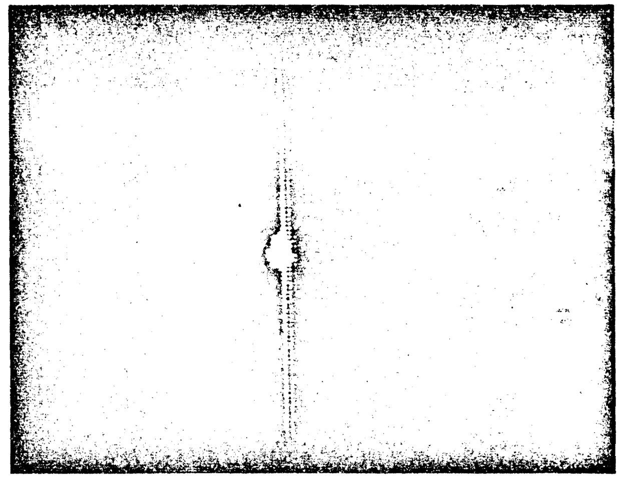
FIGURE 6
ELECTRON VARIANCE

IMAGE SPREADING

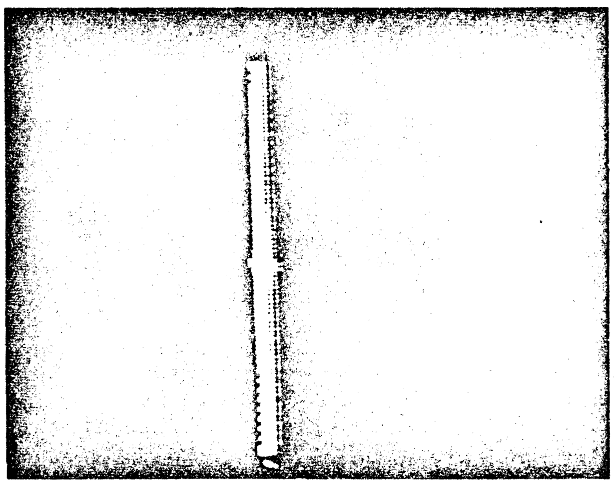
If the charge level in CCD's exceeds the capacity of the wells, the charge will be free to spread laterally away from the point of generation. Unless a means of preventing this charge from reaching the output is provided, a spread, or "bloomed" image will result. In silicon diode array targets, the charge diffuses radially outward from the point of generation until unsaturated diodes are reached or until it recombines. In CCD's the direction of spreading will be influenced by the structuring of the array and by the readout technique. In the interleaved transfer structure utilized by Fairchild, channel stop diffusions help to direct the charge spreading along the columns containing the saturated points. Fig. 7 is a series of photographs taken from the display of a Fairchild 100x100 element array. The upper left photo shows the true size of the optical point, which subtends about nine elements. In the upper right, the intensity of the point is increased so that spreading along two columns occurs. As the intensity of the source is increased further, charge spills out of the columns into the horizontal output register. In the photographs the direction of horizontal charge transfer is to the left. Thus charge spilling out of the columns containing the spot enters the output register in positions corresponding to columns to the right of the source. This can be seen in the two lower photos of Fig. 7.



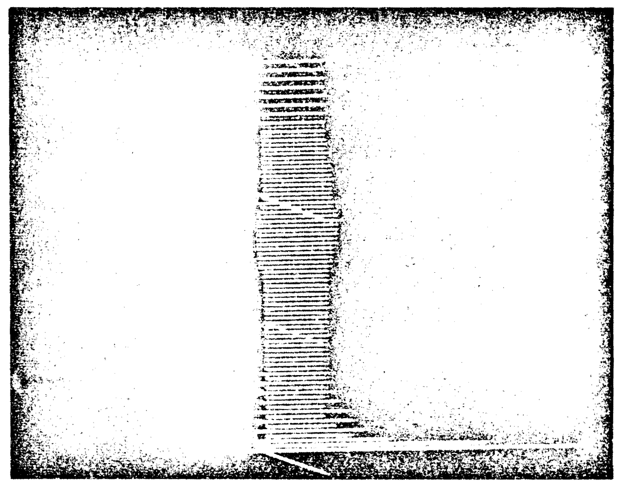
INPUT FLUX - 1.7×10^{-9} WATTS ($2854^{o}K$)



6.8×10^{-9} WATTS



4.1×10^{-8} WATTS



5.8×10^{-7} WATTS

IMAGE SPREADING IN FAIRCHILD CCAID100

FIGURE 7

If CCD's are to be useful at low light levels, they must be capable of imaging at charge levels many orders of magnitude below saturation. Hence only in extreme situations will CCD's be called upon to image points of intensity more than one or two orders of magnitude above saturation.

A goal of Phase II is that image spreading shall be limited under extreme conditions to the degree demonstrated in the lower left photo of Fig. 7.

LIMITING RESOLUTION

Limiting resolution tests were performed by the Navy review team at each of the contractor's facilities. In particular, the two extremes of the resolution versus irradiance curves were determined for each area array. This data is given in Fig. 8. Tests were performed using 100% contrast square wave bar patterns in the center of the array, oriented perpendicular to the high speed transfer direction. Resolution is expressed in line pairs or cycles per millimeter, to normalize for the various array sizes. The TI array exhibited the highest resolution 16 cycles/mm). The Fairchild array, limited by a coarser horizontal pitch (1.6 mils) resolved only 12 cycles/mm, but had the widest dynamic range of all of the devices demonstrated. It should be noted that none of the imagery produced was limited by temporal noise. All of the imagery was limited by factors not fundamental to CCI operation. For example, the camera used to demonstrate the RCA array had insufficient video gain to make noise discernible. Thus the display was limited by contrast rather than SNR (Signal-to-Noise Ratio).

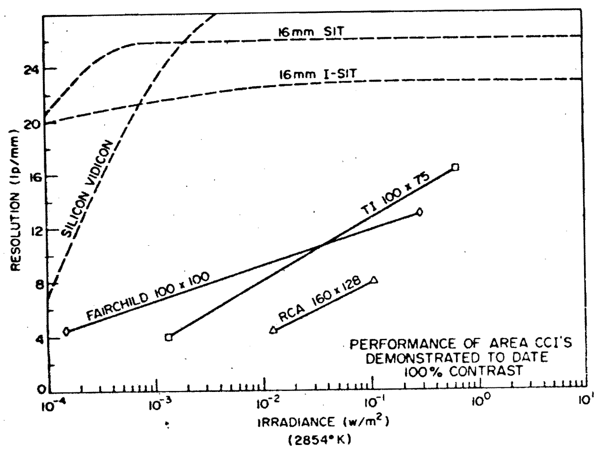


FIGURE 8
MEASURED CCD RESOLUTION

LOW LIGHT LEVEL PERFORMANCE PREDICTIONS

INTRODUCTION

Since the performance of CCD's at low light levels has been limited thus far by nonessential problems that can be eliminated in future CCD imagers, a comparison of current CCD data to that of vacuum camera tubes, as is done in Fig. 8, is not useful in assessing the future role of CCD's in night vision technology. At this time, it is more appropriate to rely on CCD performance predictions based on limitations imposed by fundamental temporal noise sources. Such predictions can be used to determine the levels of CCD noise that will limit CCD performance to that of various conventional camera tubes.

Carnes and Kosonocky have reported[3] a model to determine limiting resolution as a function of irradiance for various noise limits. As a result of their analysis they conclude that a 500x500 CCD imager with a fixed noise level on the order of several hundred electrons per well per frame should achieve performance "roughly comparable to that of the I-SIT (Intensified-Silicon Intensified Target) tube." However, a careful study of the analysis indicates that several errors and questionable assumptions have been made, and that the acceptable CCD noise level for I-SIT performance is not nearly as high as indicated by Carnes and Kosonocky. The following is a description of each of the corrections and modifications that should be made to the analysis used by Carnes and Kosonocky. Following this list of changes, the equations used in their analysis are restructured, and resolution versus irradiance curves are plotted for various assumed noise levels, based on the revised model. Also plotted is measured performance data for I-SIT and SIT camera systems.

CHANGES TO RESOLUTION VS IRRADIANCE MODEL

1. The Carnes and Kosonocky analysis is based on an assumed SNR threshold that is much higher than should be applied to the resolution of bar patterns. Tests on I-SIT camera systems conducted at the Naval Air Development Center show that bar patterns with bar lengths extending over one-third of the picture height can be resolved at mean photoelectron rates as low as 20 per second in a square resolution cell defined by the bar width. This result is very close to predictions made by Rosell[4] which are based on recent psycophysical experiments. This threshold is much lower than the 250 electron per second threshold implicit in the photon shot noise analysis of Ref. (3). This discrepancy results in an overestimation in the required irradiance for a given resolution level by a factor of 12.5 for the case of 100% contrast photoelectron noise limited imagery. For the case of imagery limited by a fixed noise source,

the overestimation is $(12.5)^{1/2}$. Thus, the Carnes and Kosonocky analysis reduces the irradiance gap between photoelectron noise limited resolution, and that limited by a fixed noise source by a factor of $(12.5)^{1/2}$, thereby reducing the importance of fixed noise sources in CCD's.

In the analysis that follows, the SNR threshold will be such that quantum limited resolution occurs when 30 electrons per second are generated in a resolution cell.

2. Carnes and Kosonocky have used an integration time, t = 0.1 second to calculate the signal charge. However, the fixed noise level, $\bar{N}_n$, is defined as the standard deviation of the elemental charge population, from one 1/30th second frame to another. Thus, for the fixed noise case, SNR is underestimated, and required irradiance overestimated by a factor of $(3)^{1/2}$. In the revised analysis, the signal and noise will be calculated with the same integration time, t = 1/30th second. The fact that the eye integrates over 0.1 second has already been utilized in the determination of the threshold electron rate.

3. Resolution curves will be plotted for 100%, 25%, and 10% contrast (C) bar patterns. Ref. (3) concentrate exclusively on the 20% contrast case, which tends to reduce the importance of fixed noises.

4. Absolute levels of sensor irradiance (H) are used in place of the "absorbed photon" density levels used in Ref. (3). The CCD responsivity (S) of 15 mA/watt is used. This number is conservatively based on measured Fairchild performance. However, it is expected that future devices will exhibit twice that responsivity.

5. Absolute resolution density (R), expressed in units of cycles per millimeter is used rather than resolution relative to the picture height. This change serves to normalize data of sensors of varied sizes. The maximum resolution (Rmax) is set by the assumed element spacing of one mil. The elemental area (A) is similarly set at one square mil.

6. Resolution curves are plotted for fixed noise levels ($\bar{N}$) of 1, 10, and 100 electrons. These values are selected to span an important range of noise. They are not related to specific noise sources as in Ref. (3). Also, no adjustment for correlated noise is made. Carnes and Kosonocky derate the surface state noise component by a factor of five, to account for assumed element to element correlation. While it is true that the effective level of correlated noise is greatly reduced when viewing objects subtending many CCD elements, as the object size approaches CCD element size, the masking due to correlated noise will increase beyond that produced by uncorrelated noise of equal variance. Further, there is some question as to whether the predominant surface state noise component will be correlated as assumed in Ref. (3). Thornber and Tompsett describe[5] the uncorrelated component of surface state noise that is introduced during the storage process. This may be the source of the excess noise component shown in Fig. 6, measured in a Fairchild line array operated at high charge levels, where the device is in a surface channel mode. As shown in Fig. 5, at these high charge levels, the noise in an element is not a function of the number of transfers that element must undergo to reach the output. Whereas, if the predominant interface state noise component was introduced in the transfer process, one would expect the noise in the elements furthest from the output to be much higher than that in elements adjacent to the output.

CALCULATION OF RESOLUTION VS IRRADIANCE

In the Carnes and Kosonocky approach, "the ratio of the number of photoelectrons to the number of rms fluctuations in the number per observable picture element must exceed a certain number $k_{S/N}$". Equivalently, ignoring MTF losses, limiting resolution, R, is directly proportional to the elemental SNR. That is,

$$R = R_o \text{ SNR}, \qquad (1)$$

where R_o is a proportionality constant which will be determined from the empirical threshold data. The number of photoelectrons per frame per CCD element is

$$N_S = HSAt/e, \qquad (2)$$

where

H is the image irradiance (watts/m^2),

S is the sensor responsivity (amps/watt),

A is the area of a CCD element (m^2),

t is the frame time (sec), and

e is the electronic charge (coul).

Defining contrast;

$$C = \frac{\Delta N_S}{N_S}, \qquad (3)$$

where ΔN_S is the signal, then

$$\Delta N_S = CHSAt/e \qquad (4)$$

The shot noise in the elemental charge is

$$\overline{N}_p = (N_S)^{1/2} = (HSAt/e)^{1/2} \qquad (5)$$

Combining this with the net fixed noise component, $\overline{N}$, the total noise is

$$\overline{N}_n = (HSAt/e + \overline{N}^2)^{1/2} \qquad (6)$$

Substituting equations (4) and (6) into (1);

$$R = R_o \frac{CHSAt/e}{(HSAt/e + \overline{N}^2)^{1/2}} \qquad (7)$$

R_o is determined by setting $\overline{N} = 0$, $C = 1.0$, and $R = Rmax$;

$$R_o = Rmax\ (N_S)^{1/2}. \qquad (8)$$

N_S is determined from our empirically derived threshold criterion for 30 electrons per second per resolution cell. Since at R = Rmax a resolution cell area equals that of a CCD element, the required N_S is one electron per frame per CCD element, and

$$R_o = Rmax\ (1)^{1/2} = Rmax. \qquad (9)$$

Substituting into equation (7),

$$R = Rmax \frac{CHSAt/e}{(HSAt/e + \overline{N}^2)^{1/2}}. \qquad (10)$$

The following parameters will be used in equation (10) to calculate resolution versus irradiance:

$S = 15$ mA/w (2854°K)

$A = 6.45 \times 10^{-10}\ m^2$

$t = 0.33$ sec

$e = 1.6 \times 10^{-19}$ coul

$C = 1.00$, 0.25, and 0.10

Rmax = 20 line pairs/mm

In Fig. 9, resolution versus irradiance is plotted for two values of $\overline{N}$. The dotted curves represent photoelectron noise limited performance ($\overline{N} = 0$), which is essentially the same as for $\overline{N} = 1$. The solid curves are based on an assumed $\overline{N} = 10$ electrons per CCD element per frame. The noise limited portions of the curves, determined by equation (10) are smoothed into the MTF limited asymptote, R = Rmax. The smoothing is done arbitrarily and is not based on a specified MTF curve. For comparison, measured curves on a 16 mm I-SIT system are given in Fig. 10. At low light levels, the CCD system with a noise level less than ten electrons is predicted to equal or surpass the I-SIT performance. At high light levels, the I-SIT system is limited at low contrasts by non-uniformities in the fiber optics, photocathodes, phosphor, and camera tube target. Similar non-uniformities will exist to some degree in CCD's, and will certainly reduce the performance below the predicted level.

In Fig. 11, the performance of a CCD imager with 100 electron level noise is plotted. Comparing Figs. 9, 10, and 11, it is evident that to approach the performance available with vacuum tube devices, the noise level must be substantially below 100 electrons, and to surpass present performance, noise levels must be below 10 electrons. For comparison, empirical data taken with an unintensified SIT camera system is plotted in Fig. 12. In all cases, except the low contrast, high light level condition where non-uniformities have not been factored into the CCD model, the SIT camera will surpass a CCD camera limited by a 100 electron noise source. The CCD data presented in Fig. 11 can be extended to any fixed noise level by scaling the irradiance by an amount equal to the ratio of the desired noise level to the 100 electron level assumed.

Also plotted in Fig. 11 is the measured data on Fairchild's 100x100 element array as first presented in Fig. 8. It is evident that the effective noise levels in currently available CCD's are in excess of 1000 electrons. However, as previously stated, these levels are not representative of ultimate performance. Rather, present CCD performance is limited by clocking noise, shading and non-uniformities, and by poor camera design.

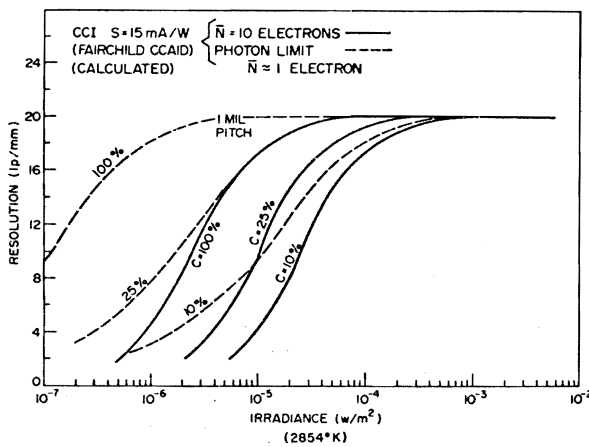


FIGURE 9
PREDICTED CCD RESOLUTION
$\overline{N}$ = 0, 1, 10

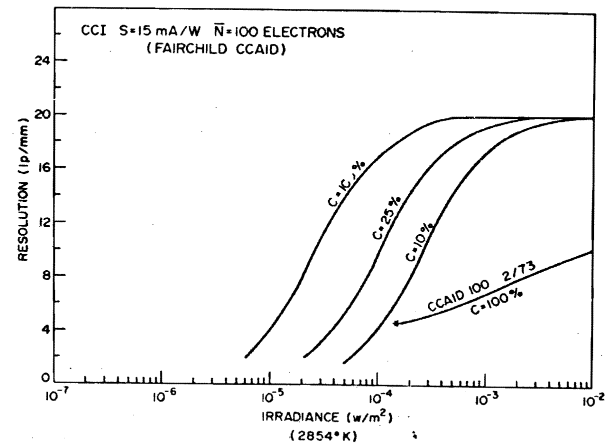


FIGURE 11
PREDICTED CCD RESOLUTION
$\overline{N}$ = 100

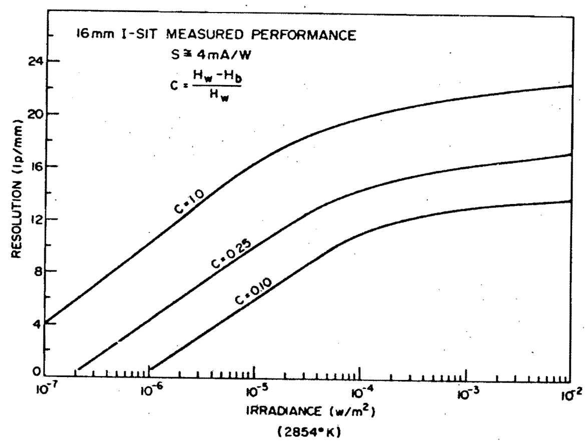


FIGURE 10
MEASURED I-SIT RESOLUTION

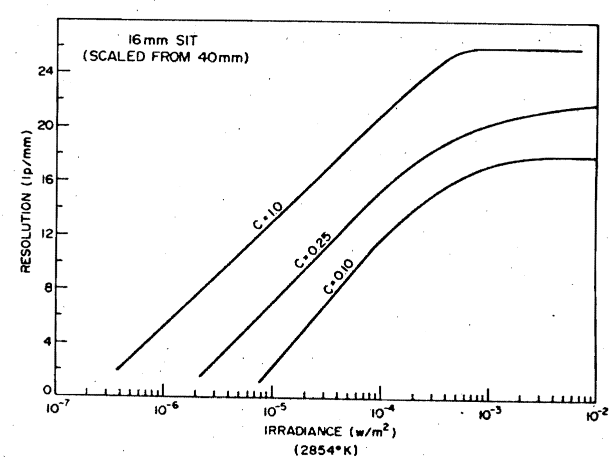


FIGURE 12
MEASURED SIT RESOLUTION

NOISE SOURCES

At present, it appears that the noise sources that will ultimately limit the performance of surface channel CCD's are associated with the problem of injecting a uniform, low noise bias charge. Experiments conducted by RCA and TI indicate that Fat Zero can be injected electrically with a charge uncertainty on the order of 50 electrons. However, it has yet to be demonstrated how the light sensitive and storage registers can be biased uniformly enough to permit operation at low light levels. The most optimistic estimates are that a bias charge variation of at least 1000 electrons may be expected from column to column. More conservative estimates indicate a level an order of magnitude higher. Since these variations are fixed spatially, signal processing can be effective in reducing them. However, it is doubtful that the column to column uniformity can ever be made good enough to permit the 100 electron level performance shown in Fig. 11.

Surface channel devices are also subject to fast interface state noise. Carnes and Kosonocky have predicted the transfer process component to be on the order of 670 electrones for large devices. It can be concluded from Figs. 5 and 6 that an interface state noise component of this magnitude is not present in buried channel operation.

The reset noise that is currently the predominant temporal noise effect in buried channel devices can be eliminated through use of the floating gate amplifier. By minimizing the floating gate capacitance, and by sensing the charge in multiple floating gate amplifier stages, the amplifier noise can theoretically be reduced to a level equivalent to a few electrons of signal. The goal of the current phase of the Navy's CCD development program is the detection of less than 40 electrons per CCD element.

Implicit in the assumption that noise levels below 100 electrons can be reached in buried channel CCD's is the requirement for cooling. To reduce the background charge to the point where a ten electron signal can be detected, cooling to temperatures below -30°C will be required. While there is no reason at this time to expect adverse effects of cooling on CCD performance, there is little experimental evidence that high charge transfer efficiency and noise free performance can be achieved with cooled, buried channel devices.

IMAGE PLANE AREA

In the analysis above, resolution density is used as a performance index so that the effect of sensing area is normalized out. Implicit in this approach is the assumption that large arrays will eventually become a reality. The importance of sensor area has not been forgotten in the Navy program. The goal of the current 12-month phase is the production of 486x 378 element arrays with a 12 mm diagonal; and the complete design of a 486x378 element array with a 25 mm diagonal. On the basis of sensor area, the latter device will be adequate for most practical camera systems.

CONCLUSIONS

Buried channel CCD's have demonstrated a greater potential for low light level operation than have surface channel devices. Surface channel devices have been shown to have intrinsic limitations which will preclude low light level operation comparable to conventional vacuum tube sensors.

Further development and experimentation with buried channel CCD's will be required to establish their effectiveness as low light level imagers. The fabrication of large area, cooled arrays, with multistage floating gate amplifiers represents a formidible goal in the continuing Navy program.

ACKNOWLEDGEMENTS

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