THE ADVANTAGES OF CCDs FOR IMAGING AT LOW LIGHT AND CONTRAST LEVELS

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ABSTRACT

Solid state imagers employing charge coupling offer significant advantages in terms of operation at low signal levels. Imaging at signal levels as low as 10 electrons has been demonstrated. This capability can be applied toward imaging at extremely low light levels with contrast in the 10-100% range, or toward imaging at light levels sufficient to fill the CCD wells with contrast below 10%. This paper discusses the potential of CCD imagers for both low light level and low contrast operation.

A comparison of the photon-in and electron-in approaches to low light level imaging is made. It is concluded that the photon-in approach requires a noise-equivalent-signal of 10 electrons or less to equal or surpass the predicted performance of an electron-in CCD. The effects that limit low contrast operation of beam scanned imagers are discussed. The TDI (time-delay-and-integration) CCD is capable of the extremely low contrast performance by virtue of the spatial noise averaging inherent in the TDI process. It is expected that a TDI device with 128 steps of integration will facilitate imaging at contrast levels less than one tenth that of conventional imagers. This degree of improvement could extend the viewing range through the atmosphere by a distance equal to about 60% of the meteorological visibility range.

INTRODUCTION

It has long been recognized that imagers using the charge coupling concept are potentially capable of operation at much lower signal levels than comparable vacuum sensors. Preamplifier rms noise is roughly proportional to the total capacitance between the output mode and ground. Typically, a vidicon camera tube/preamp combination have a stray capitance $C_s = 25$ pf, whereas the stray capacitance on an on-chip gated charge amplifier is about 1/4 pf, or 1% of that of the vacuum sensor. Thus, the CCD should be capable of a SNR (signal-to-noise ratio) about 10 times higher than that of the conventional camera system.

The sensitivity is improved further with the use of a floating gate amplifier, where the output capacitance is that of a floating electrode structure rather than of a diffusion. Effective capacitance as low as 30 femptofarads has been demonstrated with a floating gate amplifier. Since the floating gate senses charge nondestructively, the signal can be amplified through a series of floating gate structures, referred to as the DFGA (Distributed Floating Gate Amplifier) wherein the signal is increased in proportion to the number of stages, M, while the noise increases as $M^{1/2}$. DFGA amplifiers with 12 stages have been built and demonstrated to have noise equivalent charge levels less than 20 electrons per element per frame.

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Thus, a CCD imager may be more sensitive than a conventional camera system by a factor ranging from 10, in the case of a gated charge integrator amplifier, to over 100, in the case of a DFGA. This advantage can be employed in one of two ways. The most straightforward approach is to use the sensor to image at lower light levels. A less obvious but perhaps more fruitful direction is to utilize the increased dynamic range offered by a higher SNR to enhance low contrast, bright light level imagery. Both approaches will be addressed herein.

LOW LIGHT LEVEL IMAGING

Two approaches to employ CCDs for night vision enhancement are currently being pursued: photon-in and electron-in imaging. The photon-in approach capitalizes on the near infrared response of silicon while placing extreme demands on the preamplifier. The electron-in approach overcomes the preamplifier noise limitations, at the expense of the added complexity of installing and operating a CCD in a high voltage vacuum tube. In the following analysis, the performance of both approaches are compared on the basis of predicted temporal SNR.

If all of the spatially fixed noise sources, such as dark current nonuniformity and clock feedthrough can be eliminated, the video SNR can be expressed (ref. 1) as:

$$\mathrm{SNR} = \frac{CN_H}{(N_H + N_2^{\,2})^{1/2}}\ , \text{ where} \tag{1}$$

C is the image contrast, defined as

$$C = \frac{E_H - E_L}{E_H}\ , \tag{2}$$

N_H is the highlight charge level per pixel (picture element) and N_2 is the temporal noise introduced by the preamplifier. The highlight charge level is given by:

$$N_H = \frac{E_H SAt}{e}\ , \tag{3}$$

where E_H is the image highlight irradiance (W/m^2 - 2854K), S is the responsivity (A/W - 2854K), A is the pixel area (m^2), t is the integration time (s), and e is the electronic charge (C). If $N_H > N_2^{\,2}$, the sensor is primarily limited by the random fluctuations of the photocurrent, and is said to be "photon limited." Given any noise level N_2, there is a corresponding light level below which the sensor is limited by the preamplifier noise. However, as N_2 is reduced, this occurs at a lower SNR. At some point, the SNR becomes so poor that further reduction of N_2 is of little practical value. While it is difficult to assign an absolute value for this point, it is instructive to assess the subjective quality of television images at various SNRs. In figure 1, an aerial photograph is imaged using a television camera system with a controlled level of additive temporal noise. The system bandwidth is limited at 4 MHz to simulate a 500 x 500 element array operated at 30 frames per second. The signal is defined as the difference between the highlight and lowlight levels in the central area of the image, and the rms noise is measured over the 4 MHz bandwidth. The displayed image is photographed using an exposure time of 1/8 second.

It is the author's opinion after examining figure 1 that performance at SNR levels below unity is of little practical value and should not be given much weight. If $N_2 = 0$, a SNR = 1 is achieved when $N_1 = 1/C^2$. Adding a fixed noise level $N_2 = 1/C$ reduces the SNR by 3 dB. Thus, if C = 1, the noise level must be less than one electron per pixel per frame, if the sensor is to be considered "photon limited."

This level of noise can only be achieved using CCDs in the electron bombardment mode, such as is used with silicon diode array camera tubes. Ideally, one signal charge is generated for each 3.5 eV of electron energy. Electron gains of about 1000 can be achieved with an acceleration potential of 10 kv. This gain reduces the effective preamplifier noise proportionately, so that even a CCD with a preamplifier noise level of hundreds of charges can be made to be "photon limited." This reduction in noise possible with electron bombardment is offset by the lower quantum efficiency of the vacuum photocathode as compared to that of silicon. Photosurfaces used in electron bombarded silicon diode array camera tubes have a typical response of about 6 mA/W for a 2584°K tungsten source, whereas the silicon response can be over 90 mA/W, and 30 mA/W is achieved in the relatively inefficient interline transfer structure.

In figure 2, the SNR for both the direct photon-excited CCD, and the electron-excited CCD configuration are shown. Both are assumed to have 1 mil^2 pixel area, and a 1/30 second integration period. The photon-excited CCD has S = 30 mA/W, and $N_2 = 10$/pixel-frame, and the electron-excited CCD has S = 6 mA/W, and $N_2 = 0$. Figure 3 shows that at light levels above 6.2×10^{-6} W/m^2, the direct photon-excited CCD yields a higher SNR for any scene contrast. The electron-excited CCD results in a higher SNR than the photon-in CCD at irradiance levels below 6.2×10^{-6}. Except at unity contrast, this seeming advantage at low light levels is of little practical importance.

Previously, comparisons of photon-excited and electron-excited CCDs (refs. 1-4) have been made on the basis of limiting resolution versus irradiance curves. It has been demonstrated (ref. 5) that extended bar patterns can be resolved at extremely low SNRs. If there is no MTF loss, the spatial frequency just below the bandwidth cutoff can be resolved with a peak signal to rms noise ratio less than unity. Thus comparisons made on the basis of resolution versus irradiance tend to emphasize that region of performance where the SNR is below unity, while truncating any advantage a sensor might have at higher SNRs.

On the basis of SNR, it appears that, while not "photon limited," the photon-excited CCD can be as good or better than the electron-excited CCD of comparable size, if the preamplifier noise level is not more than 10 electrons. The sensitivity of an electron-excited CCD can be increased using a minifying image section to map a larger photosurface onto the CCD array. This configuration requires a proportionately larger objective lens if the field of view and relative aperture are to be maintained. For example, a 500 x 500 element CCD with an image diagonal of about 16 mm could be used in a direct photon-excited mode with a 50 mm focal length F1.4 lens, to yield an 18° diagonal field-of-view. An inverting image section could convert such an array to an electron-excited sensor with a 36 mm diagonal photocathode. If used with a 112 mm focal length, F1.4 lens, this sensor would have the same net responsivity of the 16 mm photon-excited sensor, without the attendant preamplifier noise. It's SNR versus irradiance characteristics can be derived from the electron-excited CCD performance plotted in figure 2 by sliding those curves to the left by a factor of 5 to account for the increased photon collection of the larger lens. This would represent a significant improvement over the photon-exicted version at irradiance levels below 10^{-4} W/m^2, although the advantage comes at the expense of a much larger lens, a larger sensor package and high operating voltages.

The electron-in approach has an additional advantage in that the image section can be made gatable for use in a range-gated laser illuminated mode.

A third alternative to low light level imaging is a hybrid approach, wherein an image intensifier is fiber-optically coupled to the photon-in CCD. This approach attains all of the advantages of the electron-in mode without the complexity and reduced yield of an integral structure, at the expense of some MTF degradation in the fiber optic coupling.

LOW CONTRAST IMAGING

The photon-in approach to low light level imaging requires that the sensor be capable of operation at signal levels several orders of magnitude below saturation without background charge, or fat zero. Operation at low signals with a high level of fat zero is equivalent to imaging at a low scene contrast. Conventional vacuum tube sensors are limited in their ability to reproduce low contrast signals by several factors, all of which might be overcome in a CCD imager:

Photocathode Shading

In electrostatically focused image tubes, the responsivity decreases from the center radially outward, by as much as 50%. When imaging with such a tube, any attempt to suppress the background level and stretch the small signal level, results in a "portholing" effect, where only the center of the field-of-view is useful. CCD imagers do not exhibit severe shading of responsivity.

Mesh Interference

In many vidicon readout tubes, the accelerator mesh modulates the signal, superimposing a fine grid with amplitude as high at 10% of the signal. This mesh is usually unnoticed until one attempts to increase the contrast. The CCD readout, of course, does not require such a mesh.

Dark Current Nonuniformities

In silicon diode array target tubes, the dark current is usually shaded and is often mottled with fine grain detail, with peak-to-peak variations as high as 5% of the saturation level. The small size of the

CCD imager facilitates thermoelectric cooling to reduce dark current and dark current variations to negligible levels.

Transmission Variations

Every image plane in a sensor is subject to fine grain variations in transmission or gain, so that the signal is modulated proportionally. This is particularly a problem in low light level sensors containing several interfaces, such as fiber-optic surfaces, phosphor screens, microchannel plates, photocathodes, and storage targets. Again, peak-to-peak variations as high as 10% of the mean are not uncommon. CCD imagers have transmission variations to some extent, especially where imaging through several refractory gate levels. However, preliminary tests on a dual level polysilicon gate imager shows column to column nonuniformity less than 5%, and spatially random variations less than 3% peak-to-peak at room temperature.

Temporal SNR

The maximum SNR in a vacuum camera system is limited by the maximum signal current and the preamp noise equivalent current. For vidicon type readout tubes the former is of the order of 200-500 nA and the latter is about 5 nA. Thus, a maximum temporal SNR of 40 dB can be achieved. In the CCD sensor with a noise equivalent signal of 200 electrons or less, and a maximum charge of 200,000 electrons or more, the maximum SNR is dictated by the signal to shot noise ratio, which at 200,000 electrons is about 53 dB, or 13 dB above the maximum achievable SNR of the conventional system.

From the above it is apparent that the limiting factor for low contrast operation of CCDs will probably be variations of gain due to nonuniform transmission. Assuming 2-3% uniformity can ultimately be achieved in staring arrays, the CCD sensor will exhibit more than three times improvement at low contrast levels. Beyond that, TDI (Time Delay and Integration) devices can be used to further improve uniformity. Assuming random spatial variation of transmission over the array, the nonuniformity can be reduced as $M^{-1/2}$, where M is the number of TDI steps, a net variation of less than 0.3% might be achieved, thereby reducing the low contrast threshold on order of magnitude below what might be achieved in a staring array, and more than an order of magnitude below what is achieved in conventional tubes.

In applications where performance is limited by contrast reduction due to the atmosphere, an improvement in uniformity and hence low contrast rendition manifests itself as increased range. Assuming an exponential decay of contrast through the atmosphere, the liminal contrast C_L is determined from the inherent contrast C_o, the atmospheric extinction factor σ, and the range R.

$$C_L = C_o e^{-\sigma R}$$

If C_L can be reduced by a factor K, the range can be increased by a factor

$$\Delta R = \frac{\ln K}{\sigma}$$

Given a clear atmosphere, with $\sigma = 0.17\ Km^{-1}$, and a tenfold improvement in uniformity (K = 10),

$$\Delta R = 6 \ln 10 = 13.8\ Km$$

SUMMARY

CCD imagers are capable of lower temporal and spatial noise levels than conventional camera tubes, and are therefore capable of operation at lower light and contrast levels. The photon-in CCD with temporal noise equivalent signal of 10 electrons will yield low light level performance comparable to that of an electron-in CCD with a conventional photocathode. The TDI-CCD is capable of operation at threshold contrast levels over an order of magnitude below conventional vacuum tube sensors, at light levels sufficient to nearly saturate the sensor. This level of improvement can manifest itself as an increase in effective viewing range through the atmosphere by a distance which is nearly 60% of the meteorological range.

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LIST OF FIGURES

Figure 1. Television imagery produced with controlled levels of SNR. Signal is defined as the maximum excursion between the highlights and lowlights, and the rms noise is measured over the 4 MHz bandwidth used to simulate a 500 x 500 element CCD camera.

Figure 2. Comparison of SNR versus E_H plots for the photon-in and electron-in CCD imagers. Both have 1 mil^2 pixel area, and the integration period is 1/30 sec.

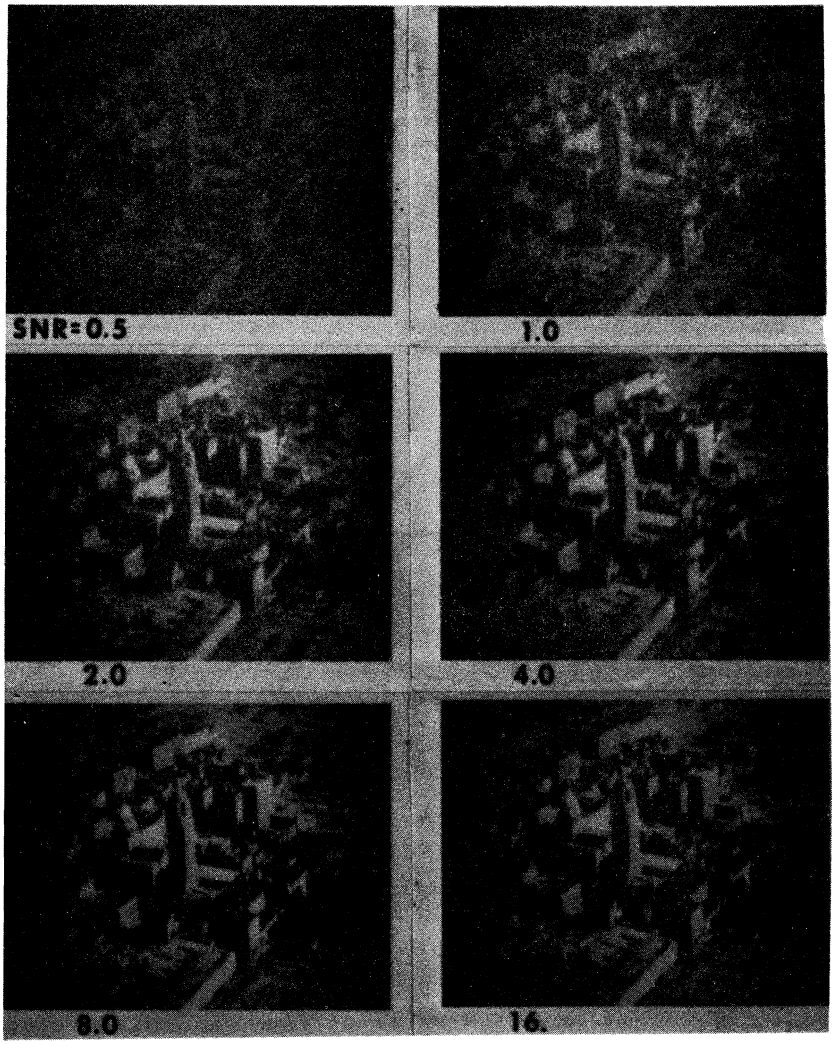

Fig. 1

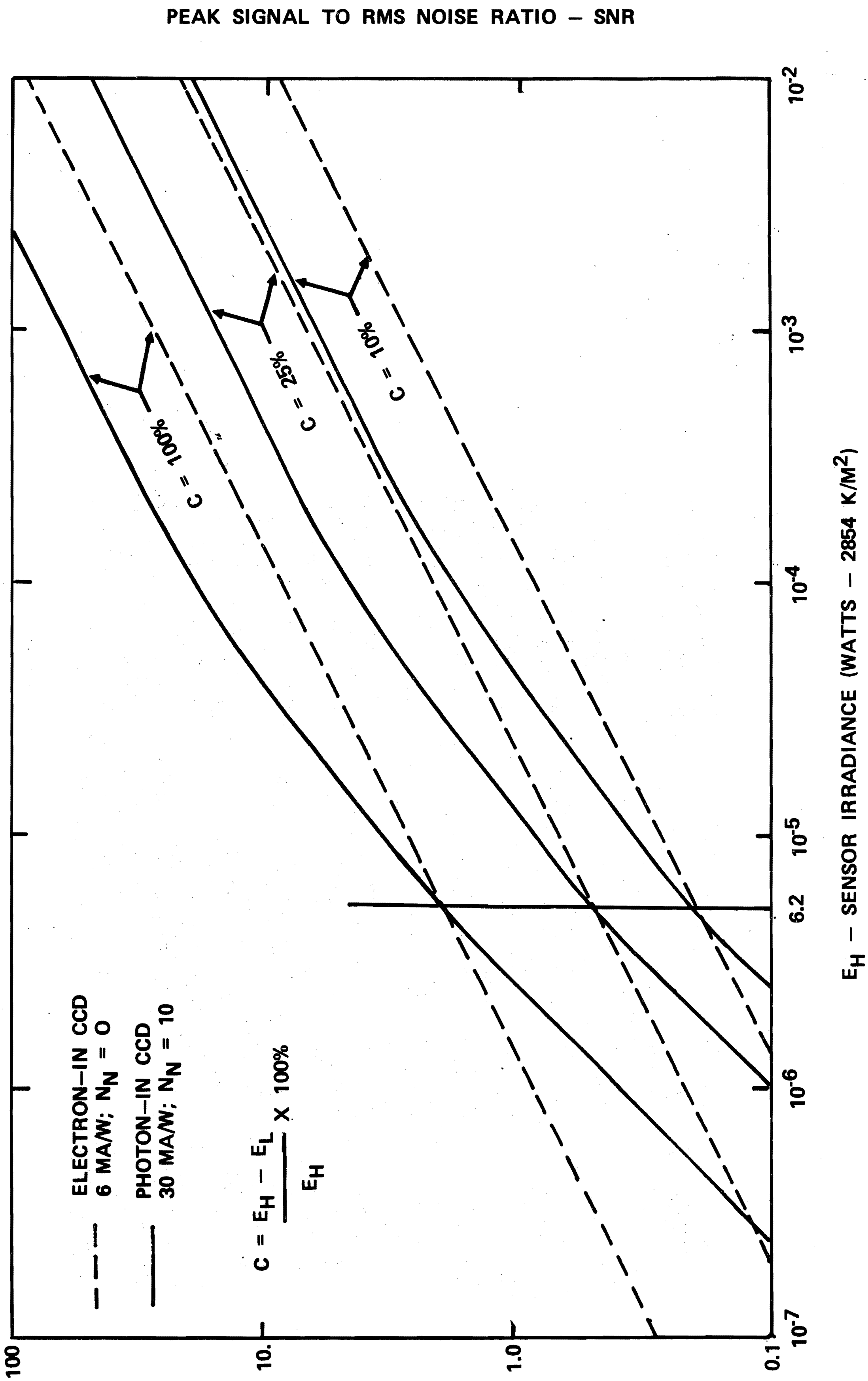
PEAK SIGNAL TO RMS NOISE RATIO – SNR
100
10.
1.0
0.1
10-7
10-6
6.2
10-5
10-4
10-3
10-2
E_H – SENSOR IRRADIANCE (WATTS – 2854 K/M²)
ELECTRON–IN CCD
6 MA/W; N_N = O
PHOTON–IN CCD
30 MA/W; N_N = 10
C = (E_H – E_L)/E_H X 100%
C = 100%
C = 25%
C = 10%

Fig. 2