APPLICATIONS OF CCD IMAGERS IN LOW LIGHT

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ABSTRACT

Current low light television sensors and CCD imagers together with some of the tasks that low light imaging systems perform are reviewed. A model of the operation of a low light sensor is extended to cover, in a unified treatment, both current low light television systems and proposed solid state low light systems, and this model is used to indicate the expected performance of some selected systems. The state-of-the-art of existing remote view sensors and the low light potential of CCD, EB-CCD and EB-CID are discussed together with some possible applications.

INTRODUCTION

Low light level imaging devices are currently being applied to a wide range of activities. These include underwater exploration, low dosage X-ray fluoroscopy and optical systems operating at night using reflected natural or artificial radiation. The devices currently used in these systems with particular reference to night operation will be reviewed together with the current state-of-the-art in CCD device technology, including associated devices with electron beam pre-storage gain. Simple modelling of the performance will be applied to typical night operating systems so that important parameters of device and system are highlighted. CCD devices are steadily becoming larger, more sensitive, more sophisticated, while demanding ever higher levels of technology. The future of CCD and associated devices is discussed with reference to night viewing systems.

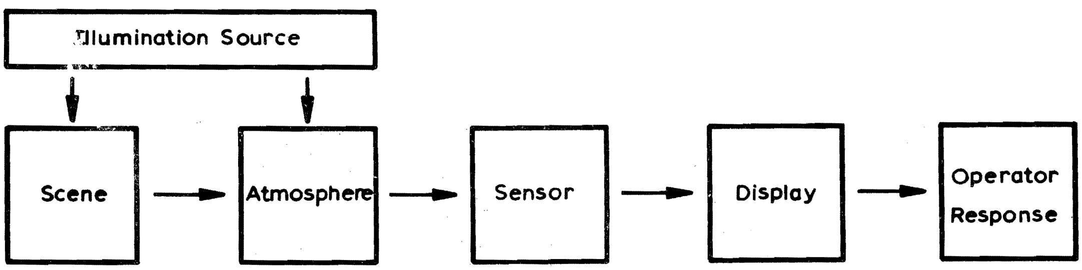

FIGURE 1. Basic electro-optical system.

SYSTEM REQUIREMENTS

The operation of a particular electro-optical imaging system involves the essential steps shown in figure 1. Figure 2 shows a typical distribution of natural light levels at night. A clear night with full moon and an overcast moonless night correspond to 2.10^{-1} Lux and 10^{-4} Lux. If operation is required for at least 80% of time at night, then adequate

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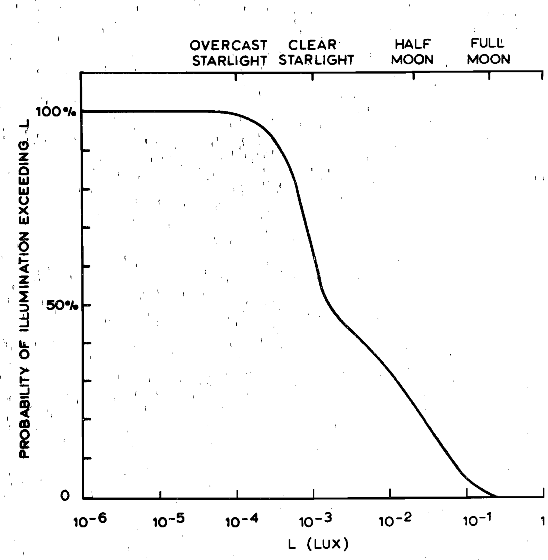

FIGURE 2. Cumulative probability of night illumination.

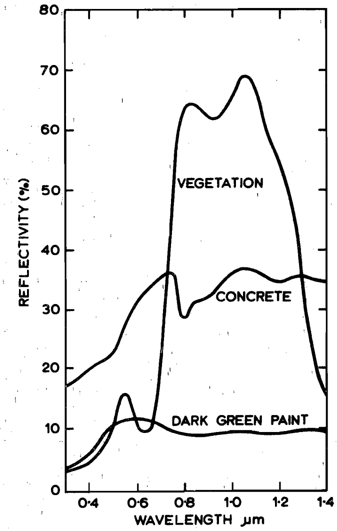

FIGURE 3. Spectral reflectivities of some typical surfaces.

performance at 5.10^{-4} Lux i.e. one half of clear starlight, is needed. Visual and low light systems are both affected by atmospheric transmission and scattering which must be taken into account when predicting system effectiveness. The contrast is also a function of the spectrum of the ambient illumination, the spectral reflectivity of the scene components and the spectral response of the photodetector. Of special importance is the very large increase in reflectivity of vegetation in the near infrared as shown in figure 3.

TABLE 1. Important Characteristics of an Electro-optical System

Sensor	System
Spectral response	Size
Sensitivity	Weight
Dynamic range; overall/intrascene	Power/Cooling requirements
Resolution/MTF	Field of view
Dynamic resolution/Lag	Reliability
Bright light tolerance/Blooming	Remote/Direct view
Distortion	Cost
	Operator controls
	Mounting requirements

Selection of a sensor and associated system for a particular task should involve consideration of all the parameters listed in table 1. For example, a flying aid must have minimum operator controls, be unaffected by bright lights, have low distortion, have high sensitivity and be reliable. On the other hand, for a security system distortion is unimportant, cost is a most significant parameter and if some artificial illumination is available a high sensitivity may not be needed.

In principle, a low light television system may be produced by coupling a direct view sensor to a conventional daylight television camera tube but this seldom produces a system of high quality owing to the poor overall MTF obtained. Current low light television systems consist of a single stage inverting intensifier coupled to a special purpose camera tube incorporating an image section and a scanning section within the same envelope.

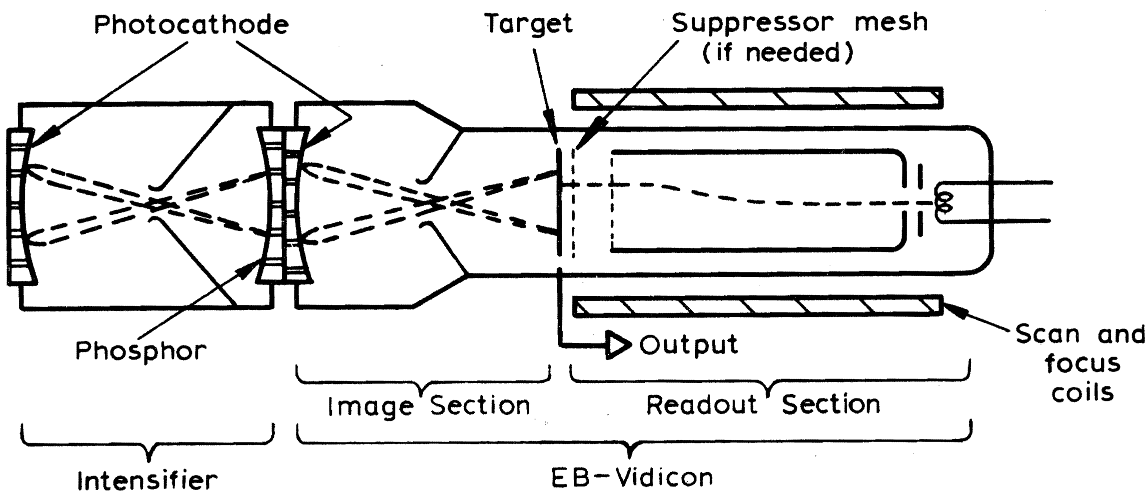

FIGURE 4 (a). Intensifier - EB Vidicon.

EB Vidicon

Two tube types use an electron bombarded target as shown in figure 4(a). The target has pre-storage gain produced by electron multiplication of photoelectrons accelerated to high energies (up to 15keV) in the image section. The target charge pattern resulting from this bombardment is read out using conventional vidicon electron beam scanning. The two tube types differ principally in the choice of target material. The peak signal current for all the tubes is typically 300nA.

Low density KCl on a supporting layer of Al_2O_3 is used in the SEC vidicon. The gain mechanism is secondary electron multiplication in the voids within the target and a typical target gain is x 200. This tube is now used only for certain specialised systems requiring long image storage times, as the target is fragile and susceptible to damage in overload conditions.

A silicon diode array target is used in the tube known variously as the SIT, SEBIR or EBSICON. The gain mechanism is internal secondary electron-hole pair generation in the silicon, and target gains can be x 2000. It is rugged and has almost completely replaced the SEC vidicon.

Image Isocon

This tube works on a very different principle. As shown in figure 4(b) the image section is magnetically focussed and the accelerating voltage is low, about 600 volts. The target material is a thin self-supporting layer of semiconducting glass where incident photo-electrons produce secondaries with a gain of about 3. The signal currents flowing in the target are too low (<1 nA) to be amplified directly in a vidicon scanning system and therefore scattered electrons, produced simultaneously with target discharge, are returned down the axis of the tube and multiplied in an electron multiplier. The output signal current can be 50μA. This tube is very much more complex than an Ebsicon and is only made in relatively large formats, i.e. >36mm diagonal.

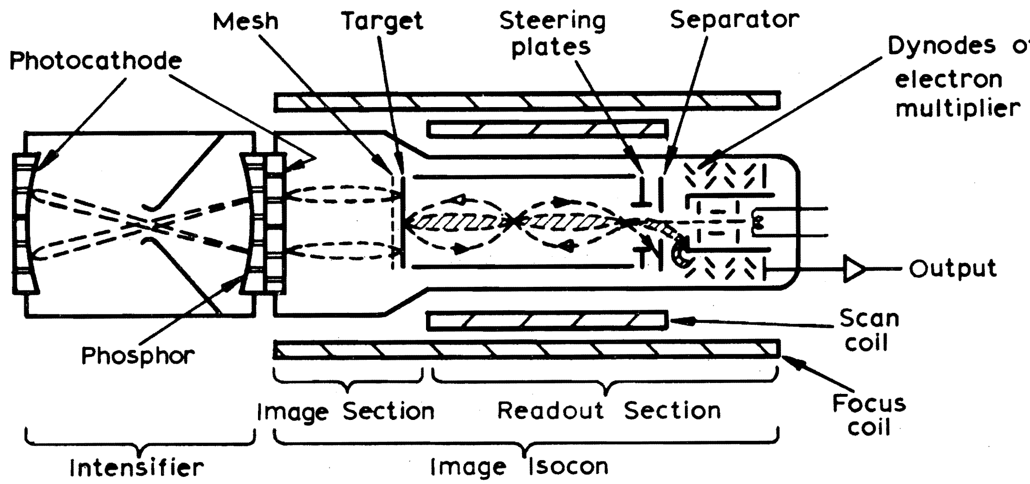

FIGURE 4 (b). Intensifier image isocon.

CCD

The simple versions of CCD imagers, whether with surface or buried channel technology, frame or interline transfer organisation, front or back side illumination, are not suitable for low light level operation. While the quantum efficiency can be high their small physical size and significant noise level mean that their signal to noise ratio is insufficient for this purpose without improvement using cooling and the lowest noise technologies. The resulting package will therefore be more complex than the 'standard' area CCD.

EB-CCD

An alternative is to introduce pre-storage gain by detecting the light with a photocathode and then accelerating the photoelectrons so that many secondary electrons are generated when they strike the CCD (ref 1). Any of the three basic electron-optical imaging systems shown in figure 5 can be used. Only the inverter system allows magnification or demagnification. The availability of pre-storage gain (offset by the lower quantum efficiency and reduced spectral range of a photocathode) result in a device less critical to CCD noise than in the first case considered, and either surface or buried channel operation can be considered.

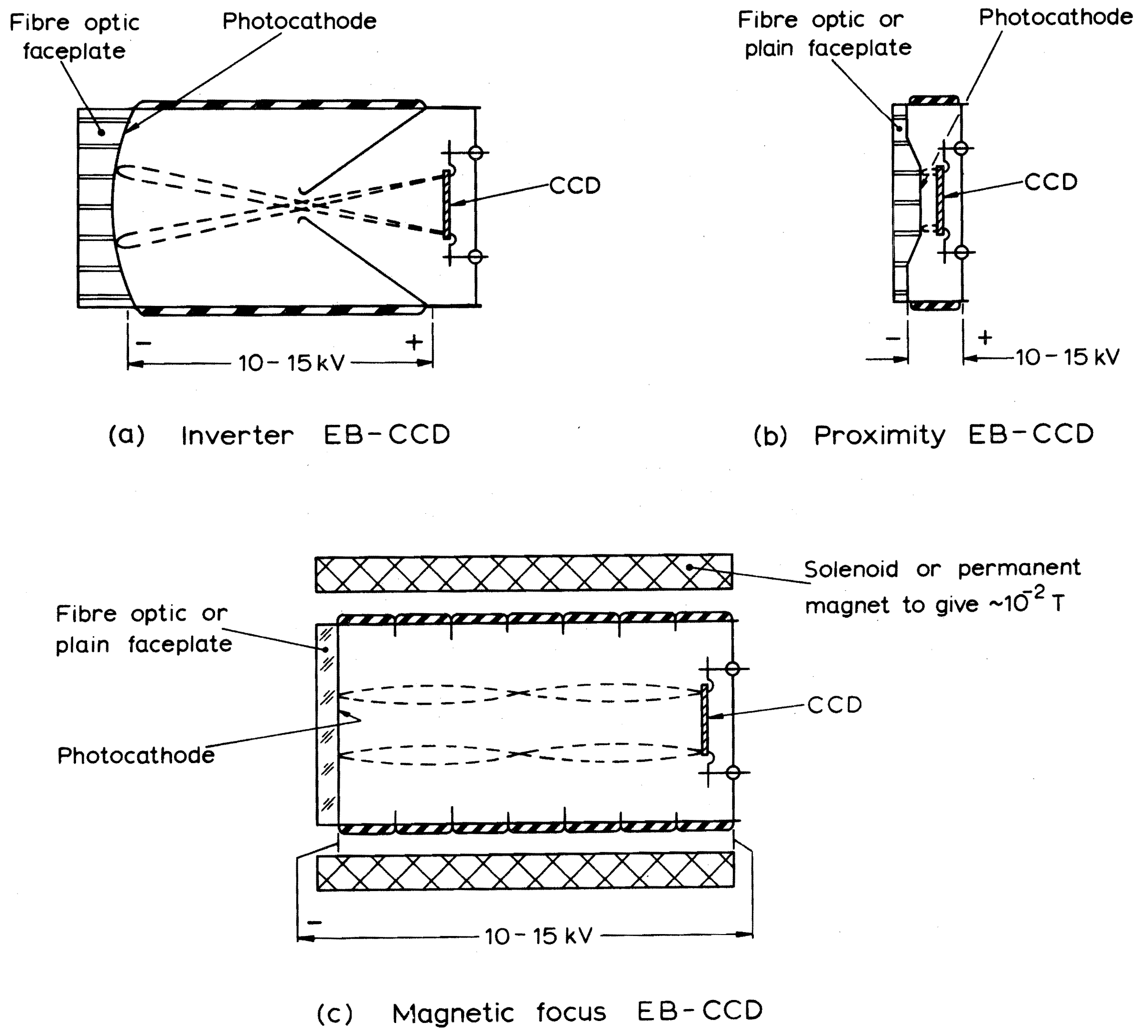

FIGURE 5. EB - CCD.

EB-CID

Pre-storage gain is essential if a CID is to be used to obtain low light level performance as the noise levels are inherently higher than for a well designed CCD. Any of the configurations shown in figure 5 can be used with a CID. Michon and Burke (ref 2, 3) have described CID imager operation. The basic mode of operation, where signal readout is achieved by X-Y addressing of MOS storage capacitors, was subject to noise and speed limitations in early technologies based on sequential injection. Parallel injection has helped to improve performance. In its high light level version the CID array is made on an epitaxial layer of silicon so that the epitaxial/substrate junction can collect the carriers freed by the CID readout process. If these carriers are not collected or otherwise quickly removed from the pixel site, they can be recollected during the next integration period and the readout will be only partly destructive. An epitaxial/substrate junction cannot be used in the EB input mode in the backside-illuminated configuration. One solution is to use a grid of diffused conductors to provide localised charge collection.

MODELLING IMAGER PERFORMANCE

The Rose (ref 4) model for detection of objects by a human observer has been applied to image intensifiers (ref 5), camera tubes (ref 6) and CCD imagers (ref 7). In each case the concepts peculiar to that technology have decided the form of the equations so that it is difficult to make easy comparisons between the various devices on this basis. A unified treatment is therefore followed here. The system as a whole, including the human operator, is imperfectly understood so that only the simplest scenarios can be modelled.

Calculation of SNR

Rose defines the signal to noise ratio (SNR) of a sensor viewing two adjacent elemental areas (1) and (2) as:

$$SNR^2 = \frac{(n_1-n_2)^2}{n_1+n_2} = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2 2\bar{n}$$

where n_1, n_2 are the number of photoelectrons produced in an eye integration time in areas (1) and (2) and $\bar{n} = (n_1+n_2)/2$. This expression assumes Poisson statistics for the photoelectron signal so that the variance on the total signal $(n_1+n_2)^2$ is (n_1+n_2). This expression for the SNR represents the best SNR for a given sensor response characteristic.

Even the simplest sensor that can be considered, a direct view image intensifier, has a degraded SNR due to dark current characterised by n_D electrons per element and also due to the statistics of the multiplication process which can reduce the SNR by the noise factor K. In this case

$$SNR^2 = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2 2\bar{n}\left[\frac{1}{K}\,\frac{\bar{n}}{(\bar{n}+n_D)}\right]$$

For a simple TV device, such as a vidicon or a CCD operated with photon input, the readout process introduces additional noise that can be described by a readout noise per element of n_A^2 where n_A is the r.m.s. value of noise electrons in an eye integration time. If the device is operated in the EB mode, the SNR expression must also include the noise factor due to the multiplication process, the dark current n_T of the storage target and the gain G, so that

$$SNR^2 = \left(\frac{n_1-n_2}{n_1+n_2}\right)^2 2\bar{n}\left[\frac{\bar{n}}{K(\bar{n}+n_D) + (n_T+n_A^2)/G^2}\right] \qquad (1)$$

For any detector, the number of electrons generated per element per second is

$$p = \frac{aD^2}{e4F^2}\int_0^\infty T_\lambda L_\lambda S_\lambda r_\lambda d\lambda$$

where
- D is the optic diameter
- F is the optic focal length
- T_λ is the optic transmission
- L_λ is the object illumination
- r_λ is the object reflectivity
- S_λ is the sensor sensitivity
- a is the element area
- e is the electronic charge

The units chosen, whether photometric or radiometric, should be such that $L_\lambda.S_\lambda.d\lambda$ has the dimensions of amps m^{-2}. Some authors replace $4F^2$ with $4F^2+D^2$. The choice of denominator in fact depends on whether the second principal plane is curved for a low F/No lens. The expression quoted assumes that the sensor is in the focal plane of the lens. In the limited wavelength region of interest T_λ can be taken as being constant in a well designed system so that, if all integrations from L_λ, S_λ, r_λ to the equivalent wavelength independent quantities L, S, r are carried out with reference to a specified source of illumination, and if τ is the eye response time,

$$p = \frac{aD^2TLSr}{e4F^2} \quad \text{and } n = \tau p$$

The factor $(n_1-n_2)/(n_1+n_2)$ is the contrast, C, between the two areas chosen, so that the SNR determined by photoelectron noise alone is, from equation (1)

$$SNR^2 = \frac{2\tau}{e}\,\frac{C^2\bar{r}D^2T}{4F^2}aLS$$

where $\bar{r}$ is the mean effective scene reflectivity

Conventionally the elemental areas correspond to a single black and a white bar element of a bar pattern. The corresponding spatial frequency, v is then given by (see figure 6).

$$2a = 1/v^2$$

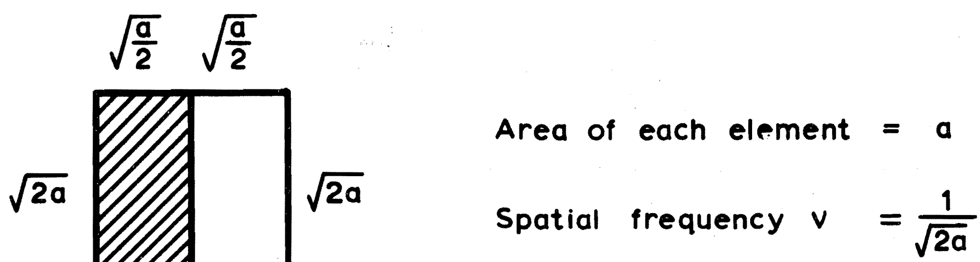

FIGURE 6. Integration areas for bar pattern.

The contrast in the image plane will be reduced by scattering, aberrations and reflections in the lens. If the lens has an MTF at spatial frequency v of M(v) then

$$SNR^2 = \frac{\tau}{e}.C^2\bar{r}.\frac{D^2T}{4F^2}.\frac{M^2(v)}{v^2}.LS = 2C^2M^2(v)\bar{n} \qquad (= SNR_o^{\,2})$$

This expression gives the SNR for an ideal sensor which has no noise sources other than photoelectron statistics. Any practical detector will be worse than this. The relevant area for the calculation of $\bar{n}$ is a.

In order to maximise the SNR at this point, firstly the sensor spectral response must be chosen to maximise the overall product $C^2\bar{r}LS$, and for many practical cases this product must be evaluated by integration. Note that the contrast is particularly important as it appears as C^2. Secondly a lens with a low F/No should be used to maximise D/F. However if reasonable resolution is required then lenses faster than about F/1.2 become very difficult, and therefore expensive. If the lens F/No is taken as fixed then the only remaining parameter is $M^2(v)/v^2$. $M^2(v)$ is only a weak function of the size of practical lenses. The interaction between lens parameters and resolution means that two application constraints can apply

(a) Lens maximum diameter is fixed. The term v^2F^2 is then constant for constant performance (apart from the effect of MTF). This implies constant angular resolution independent of lens focal length. Sensor size and lens focal length then determine the field of view.

(b) Lens F/No is fixed. This implies constant linear resolution independent of lens focal length, and for a given sensor area this implies a resolution in terms of total number of resolvable lines that is independent of lens focal length.

In both cases there is a real performance penalty inherent in using small detectors for low light level operation.

EB Vidicon

For an EB-vidicon equation (1) applies. The amplifier noise in vidicon operation is not white, but is peaked at high frequencies. However, if the assumption is made that the noise can be approximated as white noise, the familiar TV SNR expressions can be derived. TV resolution is conventionally quoted as TV lines, N, per picture height so that $a = 3A/4N^2$ where A is the total sensor area and in this and in the subsequent treatment the small effects due to non unity scan efficiency are ignored. In addition TV signal levels are measured in the video amplifier output and

Signal current $I_s = peA/a$. Target dark current $I_T = i_TA/a$

RMS amplifier noise level = I_A.

If $\bar{n}$, n_D, n_T and n_A^2 are all directly proportional to the effective integration time (i.e. number of frame times) the term in square brackets in equation (1) can be evaluated with reference to a frame time, τ_f, giving, with noise levels referred to the video

$$\left[\frac{\bar{n}}{K(\bar{n}+n_D) + (n_T+n_A^2)/G^2}\right] = \left[\frac{2efI_S}{K2ef(I_S+I_D) + (2efI_T+I_A^2)/G^2}\right]$$

where f is the video bandwidth and I_D is the dark current of the photocathode.

In TV terminology the SNR can then be written, with the sensor MTF described by m(v).

$$SNR^2 = \frac{3\tau C^2 M^2(N) m^2(N) f I_S^2}{N^2\{K2ef(I_S+I_D) + (2efI_T+I_A^2)/G^2\}}$$

Alternatively, if noise levels are referred to electrons per pixel, then the term in square brackets on the previous page becomes

$$\left[\frac{\bar{n}'}{K(\bar{n}'+n_D') + (n_T'+\left(\frac{b\tau_f I_A}{Ae}\right)^2)/G^2}\right]$$

where the prime denotes reference to a pixel of area b. With the initial assumptions stated concerning the character of TV video amplifier noise, which amounts to requiring that the noise power is proportional to element area, the number of rms noise electrons per pixel due to the video amplifier is

$$n_A' = \frac{b\tau_f I_A}{Ae}$$

CCD

CCD calculations are normally carried out in terms of noise equivalent electrons so that equation (1) can be simplified to

$$SNR^2 = 2C^2M^2(v)m^2(v)\frac{\bar{n}'v_o^2}{v^2}\left[\frac{\bar{n}'}{\bar{n}'+n_D'+n_A'^2}\right]\frac{\tau}{\tau_f}$$

where $\bar{n}'$, n_D', n_A' are referred to one pixel and a frame time τ_f, and v_o is the pixel spatial frequency.

EB-CCD or EB-CID

Equation (1) becomes

$$SNR^2 = 2C^2M^2(v)m^2(v)\frac{\bar{n}'v_o^2}{v^2}\left[\frac{\bar{n}'}{K(\bar{n}'+n_D') + (n_T'+n_A'^2)/G^2}\right]\frac{\tau}{\tau_f}$$

where $\bar{n}'$, n_D', n_A' are as in the previous equation.

Application of the Model

Performance predictions, based on SNR calculations using synthetic test objects, have been shown to be quite successful when based on a prediction of the displayed SNR. It is necessary to include an eye demand function to complete such predictions and psychophysical experiments have suggested (ref 8) that for aperiodic objects, a displayed SNR of between 3 and 4 is required for threshold detection. For periodic objects, i.e. square or sine test charts, the displayed SNR must be again about 3 for threshold detection when SNR is calculated on the basis of the area of one bar of the test pattern. Alternatively a calculation based on a bar pattern square element as in figure 6 indicates that a SNR of about 1.2 is required.

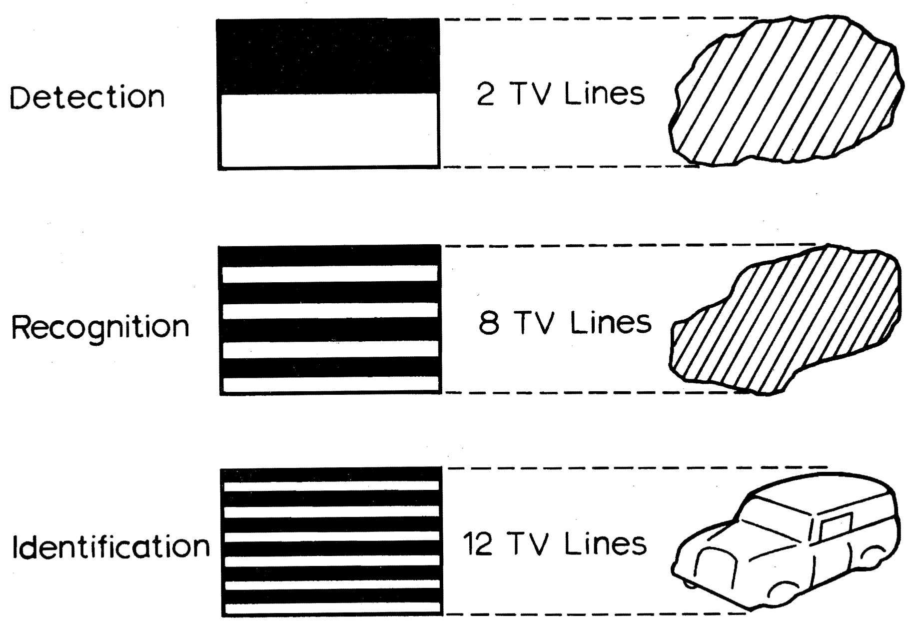

FIGURE 7. Johnson's Criteria for resolution required per minimum object dimension.

In order to translate the prediction of performance using synthetic imagery, to that using real images, criteria based on those proposed by Johnson (ref 9) are frequently used. An equivalent bar pattern is assigned to the object being viewed with a spatial period dependent on the task being performed, i.e. detection, recognition etc. The overall size of the bar pattern is determined by the minimum dimension of the object (as shown in figure 7).

While the MTF of a device and associated lens will interact with the SNR obtainable at low light levels, the performance of a system must often be competitive at high light levels as well so that the limiting resolution in either TV lines per picture height or in line pairs per millimeter is important. A high MTF at lower spatial frequencies is particularly important, and this has lead to the concept of using the total area between the MTF curve and the eye demand function as a figure of merit (ref 10).

A system designed for use in day light conditions has to contend with a typical maximum intrascene dynamic range of perhaps 1000:1, with a mean signal level variation with weather or artificial lighting of perhaps 100:1. A low light level system, on the other hand, has to operate even if sources of illumination are in the field of view. The intrascene dynamic range can then be as high as 100,000:1, and in addition the mean signal variation can span the 10^8:1 from overcast starlight to sunlight. With a range as wide as this resistance to blooming is vital, and in addition the optics and sensor must minimise veiling glare. At the very high gains possible in low light operations, the sensor should not be susceptible to damage on overload conditions. It is important to measure the system's practical limiting performance, including the observer, with synthetic test objects. The use of low contrast test patterns is a reasonable simulation of the real world and prevents undue emphasis being placed on a residual value of the MTF at very high spatial frequencies whilst stressing the need for low noise.

CURRENT INDIRECT VIEW SENSORS

Intensifier-Ebsicon

The 16mm diagonal format Ebsicon with an intensifier is being manufactured in large quantities at reasonable cost for applications where space and weight are restricted. The performance is poor at low light level due to the small photocathode area and is limited at high light level by tube and intensifier MTF. Dynamic resolution is good but the intrascene dynamic range is restricted to less than 50:1. The bright light tolerance is poor due to blooming even with the deep etched target construction. The Ebsicon without an intensifier is also used in day-light systems operating with small optical aperture and long focal lengths for high angular resolution.

Various intensifier-Ebsicon systems have been developed based on a 40mm diagonal input photocathode and a 25mm diagonal target. These systems have improved MTF with a large photocathode area and thus both low and high light level performance are improved compared to the 16mm diagonal device. The system is no longer compact or lightweight and is expensive.

Intensifier-Image Isocon

Without an intensifier the Image Isocon is widely used in medical X-ray fluoroscopy where the high SNR, resolution and intrascene dynamic range at moderate light levels are required. At the low light levels of operation required for military applications the Image Isocon alone is severely limited by lag and resolution.

When used with an intensifier, lag is no longer such a problem and at low light levels and with realistically low contrast scenes the device is limited by photon noise. In addition the intrascene dynamic range is very high (10^3 to 10^4:1) and the performance of a system with bright lights in the field of view is normally limited only by glare produced by the lens and window. It is difficult to model the Isocon as the noise sources and MTF are a strong function of light level.

CCD

In order to compete with other full TV format low light level imaging devices, the CCD must have a high intrinsic resolution, and must have low noise. Inevitably these two properties are not yet found in the same device, so it is worth considering each separately.

For low light applications the SNR depends ultimately on the total number of photons detected. The development of CCD technology is a fight to increase useful chip area at sensible yields and this demands extreme care in processing the device and particularly in devising new lithographic techniques. A 496 x 475 array has been developed (ref 11) that is compatible with 1 inch vidicon formats, having a 12.8 x 9.6 mm^2 image area. The number of elements enables the device to be used with 525 line American TV. CCD technology will be embarrassed by the different US and European (625 line) standards as, unlike a vidicon, the device dictates the possible scan formats. A 400 x 400 array has been designed (ref 12) for deep space probes where low data rates and long storage times at reduced array temperature are required. A 488 x 380 array is under development (ref 13) for TV application.

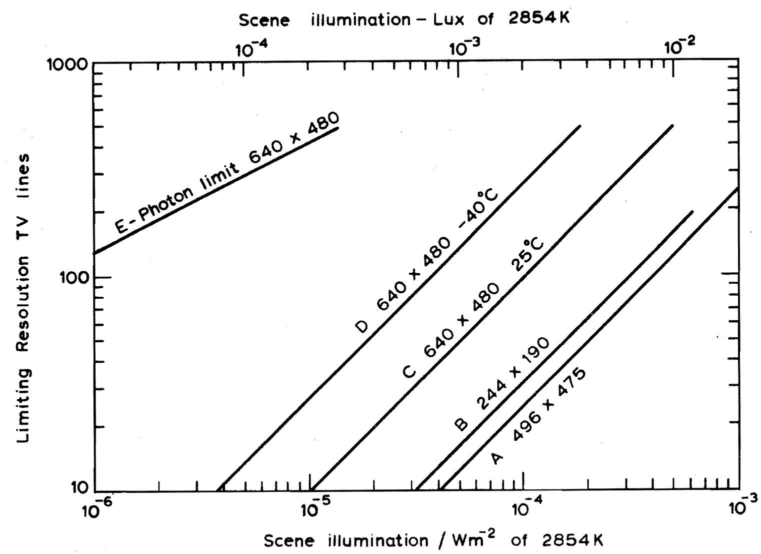

FIGURE 8 (a). Theoretical limiting resolution of CCD.

Low noise operation requires special amplifiers and cooling to -20 to -40°C. A 244 x 190 array has been developed (ref 13) that has a low light level capability. It uses 2-phase interline-transfer buried-channel technology with frontside illumination. An electronic switch selects either a distributed floating gate amplifier with a noise level of about 20 electrons for low levels, or a floating gate amplifier with a noise level less than 100 electrons for higher light levels. Blooming suppression is available. Images were obtained at input levels down to $6.10^{-6}Wm^{-2}$ ($6.10^{-4}\mu Wcm^{-2}$) corresponding to only 25 electrons on each 14 x 18μm^2 site. In order to put this in perspective, clear starlight ($5.10^{-5}Wm^{-2}$) with an F/1.4 lens of 80% transmission viewing a scene of mean reflectivity 0.4, appropriate to silicon viewing mixed vegetation and artificial objects, produces $2.10^{-6}Wm^{-2}$. If full night performance is required, then the input can drop a further order of magnitude.

The various arrays can be compared by plotting in Figure 8(a) the calculated resolution against the scene illumination. Table 2 shows the parameters chosen. A full modelling exercise would include the effects of MTF and would also need to compensate for atmospheric contrast loss and consequent modification of apparent reflectivity. However, these simpler curves readily demonstrate the area of operation, and the rank order of various devices.

TABLE 2. CCD Properties

Common to all systems	
Lens	F/1.4 with 80% transmission
Eye integration time	0.2 sec
Required SNR	3
Scene	Contrast 0.4 with 40% mean reflectance

Specific parameters	ref 11	ref 15	Prototype		
Array size	496x475	244x190	640x480		
Sensitivity/AW^{-1}	0.08*	0.037*	0.1		
Gross Sensitive Area/mm^2	$1.23.10^2$	25	$1.23.10^2$		
Gross Pixel Area/μm^2	530	540	400		
Dark electrons	10^4	10^3	$6.5.10^3$	65	0
Amplifier r.m.s. electrons	300*	40*	30	30	0
Temperature/^{o}C	24	24	24	-40	24
Curve	A	B	C	D	E

* assumed value

Curve E shows the photon noise limit for an ideal silicon sensor with 1 inch vidicon format, assuming that the required SNR is that appropriate for detection. In practice an MTF limited performance would be obtained at clear starlight and above, with some degradation at cloudy starlight. Curve A shows the projected performance of the 496 x 475 array (ref 11) assuming a readout rms noise level of 300 electrons. Curve B shows the performance of the 244 x 190 array (ref 13). The limited performance increase is due to the smaller array size, and the reduced pixel area, which offsets the advantage of lower noise operation.

It is instructive to calculate the performance of a large area array operated with a low noise amplifier. A 640 x 480 array with 20 x 20 µm pixels (480 TV lines at the Nyquist limit) would have a 1 inch vidicon format and a high intrinsic resolution. It would unfortunately not be compatible with 625 line TV. If the amplifier had a 30 electron rms noise level then operation at room temperature with a dark current of 6500 electrons/pixel would result in the characteristic of curve C. A further improvement would be obtained by cooling to $-40^{o}C$ when the dominant noise source should then be amplifier noise, giving curve D. This should now give a resolution of about a hundred TV lines in clear starlight falling to 10 to 20 lines in cloudy starlight.

All these analyses assume that the noise due to the dark current is shot noise. In general spatial noise is more troublesome. However, this noise source is extremely difficult to quantify and it is best to reject calculations involving an rms noise level less than some fraction (1 to 20%) of the dark current. All the above devices except the cooled hypothetical array could show limitations due to these variations in dark current. None of the devices considered is photon noise limited in the operating area of interest. It is this fact that makes the pre-storage gain inherent in EB-CCD or EB-CID operation attractive.

EB-CCD

Operation of only primitive EB-CCD devices has been reported so far. A 160 x 100 array has been operated in a proximity configuration with a bialkali photocathode (ref 1). Imaging was observed together with useful gain. A magnetic focus device is under development by the same team. In addition they have also modelled EB-CCD operation including MTF effects and have come to the conclusion that, while a proximity or magnetic focus device performs better than a plain CCD, an inverter with some demagnification is best. An inverter EB-CCD device has been constructed for astronomical use (ref 14), and in this case a front illumination configuration has been chosen.

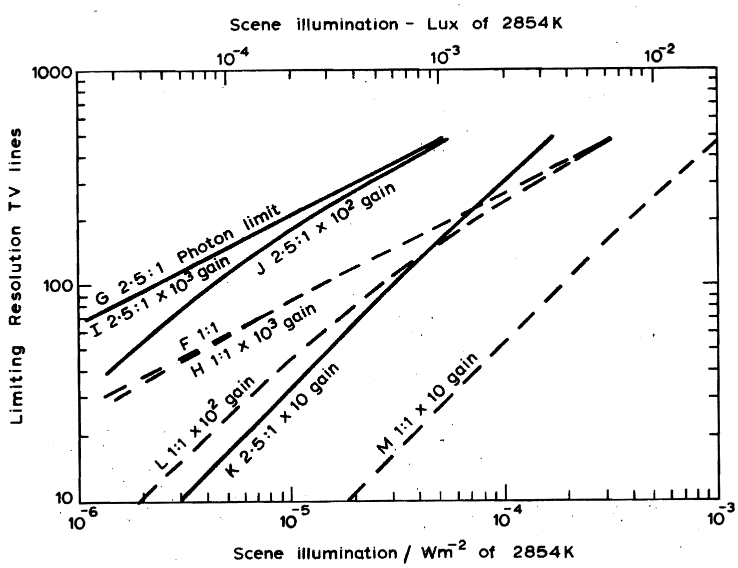

FIGURE 8(b). Theoretical limiting resolution of EB-CCD.

As so few devices have been developed it is instructive to continue the modelling exercise used for the CCD. Curves plotted in figure 8(b) are on the same basis as for figure 8(a) and the input data is given in Table 3. The photon limited case (appropriate to direct view tubes with unity noise factor) gives characteristics F and G. F is for a 1:1 device, while G has 2.5:1 demagnification so that the photocathode has a 40mm diagonal. The photocathode sensitivity corresponds to a very good S25, and photocathode dark current is assumed to be negligible.

TABLE 3. EB-CCD Properties

Common to all systems	
Lens	F/1.4 with 80% transmission
Eye integration time	0.2 sec
Required SNR	3
Scene	Contrast 0.3 with 30% mean reflectance

Specific parameters	1:1				2.5:1 demagnifying			
Array size	640x480				640x480			
Sensitivity/AW^{-1}	0.01				0.01			
Gross Sensitive Area/mm^2	$1.23.10^2$				$7.68.10^2$			
Gross Pixel Area/μm^2	400				2500			
Dark electrons	0	$6.5.10^3$			0	$6.5.10^3$		
Amplifier r.m.s.electrons	0	30			0	30		
Noise factor	1	1			1	1		
Gain	1	10^3	10^2	10	1	10^3	10^2	10
Curve	F	H	L	M	G	I	J	K

NB. pixel area is referred to photocathode

In order to use EB-CCD devices, the user must be prepared for more bulk, bigger lenses if larger photocathodes are used, and high voltages. The device is similar to an Ebsicon camera tube, but is still much lighter, smaller, and needs less power.

EB-CID

A CID, with its simpler structure involving X-Y addressing of sensor sites, should be an inherently easier device to make than a CCD. Reports published (ref 2, 3) have not given sufficient information about noise, resolution, practical cell and total areas and dark current uniformity to determine the relative ultimate status of CCD and CID. It is apparent already, however, that CID imagers show little blooming when operated with front illumination with a suitable epitaxial substrate. While sequential injection introduces a high readout noise, the alternative of parallel injection must be used with care as collection of the injected charge results in lag. A CID can be made with diffused conductors replacing the epitaxial substrate so that backside illumination becomes feasible.

In the parallel-injection backside-illuminated version the CID can be considered for EB-CID operation. The same gain as in the EB-CCD case should be obtainable, and the noise levels for the array should be comparable to reset amplifier CCD technology (100 to 1000 electrons rms). It is claimed that the dark current of a CID is lower than for the equivalent CCD. In figure 8(c) the performance of a hypothetical CID

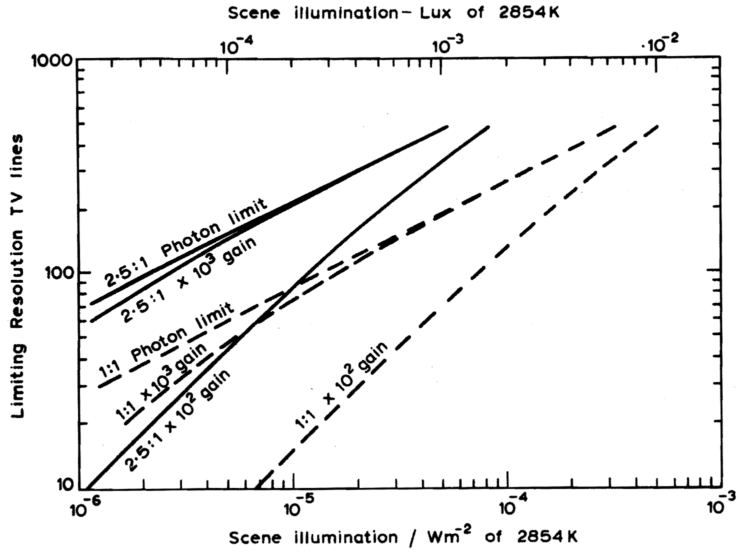

FIGURE 8 (c). Theoretical limiting resolution of EB–CID.

array is calculated using the data given in Table 4. The higher amplifier noise level means that the device must be operated at somewhat higher gain than an EB-CCD.

TABLE 4. EB-CID Properties

Common to all systems				
Lens	F/1.4 with 80% transmission			
Eye integration time	0.2 sec			
Required SNR	3			
Scene	Contrast 0.3 with 30% mean reflectance			
Specific parameters	1:1		2.5:1	
Array size	640x480		640x480	
Sensitivity/AW^{-1}	0.01		0.01	
Gross sensitive area/mm^2	$1.23.10^2$		$7.68.10^2$	
Gross pixel area/μm^2	400		2500	
Dark electrons	$6.5.10^3$	$6.5.10^3$	$6.5.10^3$	$6.5.10^3$
Amplifier r.m.s. electrons	300	300	300	300
Noise factor	1	1	1	1
Gain	10^3	10^2	10^3	10^2

APPLICATIONS OF LOW LIGHT LEVEL IMAGERS

Three basic criteria are of particular importance for low light level imaging systems. First, is an indirect (TV style) view essential, or is a TV solution competing with image intensifiers? If the system is to be indirect, then the total system cost must include the video signal transmission system and the display, and competing systems include radar and infrared imagers. Secondly is a full night/day capability required, or can reduced or zero performance in mist, fog, or cloudy starlight conditions be accepted? Finally is a very small rugged sensor essential even if system performance is then sacrificed?

Indirect view operation is essential for any form of remotely piloted vehicle (RPV). In this instance any of three tasks may be required. The 'pilot' must be able to control the vehicle and sense orientation, turning rate etc. In addition the pilot must be able to navigate the vehicle, generally by recognising suitable landmarks. This includes the ability to locate and recognise a specific object of interest. Further, the vehicle itself may be a platform for imaging devices for reconnaissance and that device might then be a TV camera. Examples of RPV's announced so far include a miniature helicopter (ref 15) and an interest in missile guidance systems (ref 16). In both cases the low size, weight and power requirements of a CCD (or either E.B. version) are vital. This applies particularly to missile guidance when the sensor is mounted in gimbals.

Another application for indirect view is when a sensor is used for air reconnaissance. Conventional sensors place such demands on space and window area that either a dedicated aircraft or an externally mounted pod is required. More compact devices allow positioning within the fuselage of a high performance aircraft with minimum performance penalty. A particular case of reconnaissance is the parachute deployed camera (ref 17) where an artillery shell contains a CCD or CID camera together with an RF transmitter. This particular application exploits the inherent ruggedness of a CCD.

Perimeter protection is an obvious application, although here a CCD competes with existing devices as small size and weight are rarely critical. However, cost is often of prime importance, so that while conventional TV (vidicons) are only a small part of the total cost, if the vidicons are replaced by current Ebsicons or Isocons, the added cost makes the resulting system commercially unattractive. The cheaper system obtained by coupling an intensifier to a vidicon has only a limited performance and as CCD's will steadily become cheaper, better, larger it cannot be long before a CCD camera undercuts and outperforms a simple vidicon camera. CCD protagonists should beware of the daylight vidicon performance however, as vidicons can give high horizontal resolution, and with slow scan up to 2000 TV line resolution has been obtained. Indeed, one special tube, the return beam vidicon, reached 10,000 line resolution (ref 18).

If full night/day capability is required then performance is critical. Unless only low resolution or reduced frame rates are acceptable, the small sensor size of a CCD makes the performance marginal at best for a significant fraction of the time at night. It is doubtful whether the semiconductor engineers would move willingly towards very much bigger devices, though the development of the electron beam lithography technique (ref 11) means that some improvement in area is possible, given enough incentive. The problem here is that commercial TV is a potentially enormous market, and low light is only a small part of it. It is therefore doubtful whether a really significant increase in size above the $120mm^2$ of current arrays is likely. The only way to increase sensitivity, if the frame rate cannot be reduced, is to use an EB-CCD or EB-CID, preferably with demagnification.

A special case is time delay and integrate (TDI) operation. If the direction and speed of image motion can be measured, then the integrating pixels can be swept during the integration period so that a particular point in the scene is integrated by the same charge packet even though the pixel used is changing. In a number of applications, particularly aerial reconnaissance and submarine periscopes (ref 16, 17) this system is attractive, and can give long integration periods in the presence of systematic image motion without producing image smear. If the low noise CCD operated at normal ambients is limited at low light levels by dark current shot noise, the SNR will increase with the square root of the TDI integration time. If the device is cooled, then amplifier noise should predominate giving a gain as the TDI integration time.

A particular feature of a CCD or CID array is the exact correlation of the time location of a charge packet with its geometric position in the array. This means that correlation techniques can be used to process the resulting video signal. A further special case is the spectral sensitivity of a CCD. This just includes the 1.06μm laser so that, like the silicon vidicon, combined 1.06μm and wide band imaging is feasible. However efficient 1.06μm imaging requires very deep depletion regions in the silicon so that only limited quantum efficiency is obtainable.

Caution must be exercised in choice of format for EB-CCD or EB-CID devices. An S20 or S25 photocathode is semitransparent to 0.9μm, and transparent beyond 0.9μm. The inverter structure is then preferred as the physical separation of the cathode and anode together with the presence of an anode cone with a small aperture prevent all but a small fraction of the transmitted light from reaching the silicon.

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