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TECHNICAL PAPER

SUBJECT : Low Light Level Solid State TV Imaging

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MARCH 2000

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Low Light Level Solid State TV Imaging

1. Introduction

Marconi Applied Technologies have developed a new low light level TV-type CCD image sensor (LLCCD). This non-intensified device has a single output and uses advanced readout technology (ART) to achieve useful imaging performance at light levels down to overcast starlight. A single sensor can now provide an improved twenty-four hour imaging capability.

This paper describes the capabilities of the new low light level imaging technology in relation to those available from other sensor types.

2. Current low light imaging technologies

One of the challenges in low light level imaging is to reduce the effects of the various noise contributions.

The three main sources of noise are :-

a. Shot noise on the signal - [$\sqrt{S}$] where S is the signal in detected electrons
b. Dark current shot noise from the CCD - [D]
c. Read-out noise from the CCD - [R]

the units being rms electrons.

Other sources of noise do exist, such as:-

d. Thermal emission from the photocathode of the intensifier, if used.
e. Scintillations from the intensifier, if used.
f. Non uniformities of response.

but are ignored here for simplicity.

The individual noise contributions can be added in quadrature, leading to a Signal to Noise ratio [SNR] of:- $S / \{N_f \,.\, \sqrt{[S + D^2 + R^2/N_f^2]}\}$
where N_f is the Noise factor.

The following table of modelled data, with figures all in electrons per pixel per 20ms field period, gives an indication of the signal and total rms noise to be expected for:

1. A conventional CCD.
2. A front-illuminated LLCCD with advanced inverted mode operation (AIMO) for low dark current and shielded antiblooming drains for minimal QE loss.
3. A similar back-illuminated LLCCD

4. An intensified CCD (ICCD), eg using an intensifier fibre-optic-coupled to the front face.
5. An electron-bombarded intensified CCD (EBCCD).

The pixel size is the same in each case.

	Conventional CCD Room temp.	LLCCD Front-illuminated -10 deg C	LLCCD Back-illuminated -20 deg C	ICCD (GaAs)	EBCCD (GaAs)
Noise Factor	1	1.4	1.4	3	1.1
1/4 Moonlight Signal	12	19	40	16	16
Shot Noise	3.5	4.4	6.3	4	4
Read-out Noise	200	0.2	0.2	negligible	1
Dark Noise	17	1	1	negligible	negligible
Total Noise	201	6.3	9.0	12	4.4
Signal to Noise	.06	3.0	4.4	1.3 (2.3)*	3.6

The analysis assumes that the noise bandwidths for each camera are equal to the Nyquist bandwidths for each of the sampling axes (lateral, vertical and temporal). The ICCD SNR improves (as shown *) if phosphor lag is included.

The results firstly show that the performance of a conventional CCD is totally dominated by the 200 electron read-out noise. Changing the CCD to the new low-light type sees the noise reduce to 6 electrons and the SNR is now higher than an ICCD. A back-illuminated low-light type would be even better with an SNR higher than an EBCCD.

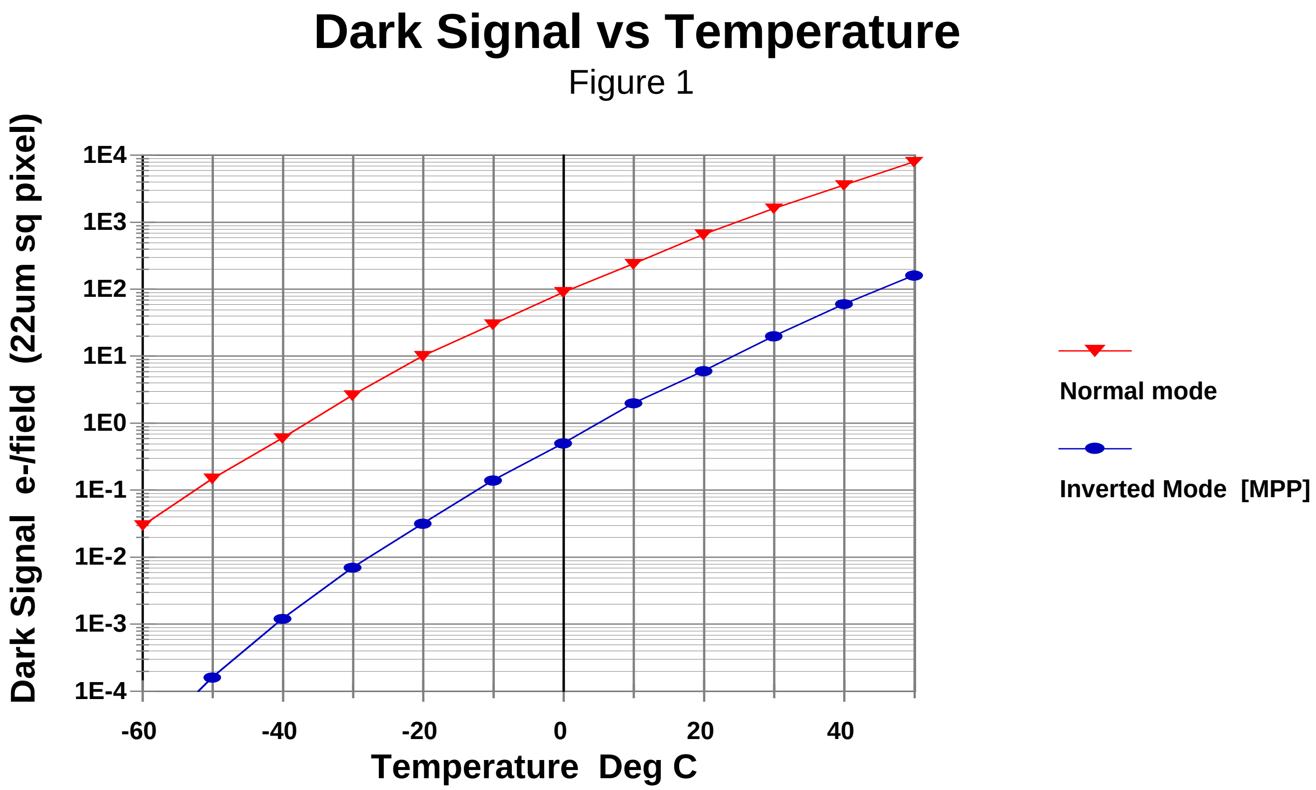
This improved performance is now described in more detail, starting with the approaches used to date to achieve essentially very low noise operation.

2.1 Slow scan CCD imaging:

Slow scan imaging systems generally use cooled detectors to reduce the dark current, and hence the dark current noise. The sensors are also read out very slowly to reduce the system bandwidth and hence also the read-out noise.

For very long integration times, such as those used in astronomy, the sensor is cooled to cryogenic temperatures, and the large pixellated focal plane arrays are read out at typically 20 kHz to give noise of a few electrons and thereby high-quality images.
In applications where cryogenic cooling is not practicable, eg TV, the dark current can be reduced using an Inverted Mode CCD (sometimes called Multi-Phase-Pinned, or MPP), in which the surface generated dark current is removed, resulting in an almost two order of magnitude improvement.

Figure 1 shows a typical dark current (in electrons per pixel per field) from a typical 'standard mode' and 'inverted mode' CCD and the dependence on temperature.



2.2 Multi-read-out ports

As the framing rate increases and the integration time becomes shorter, the contribution of the dark current noise reduces, and the read-out noise begins to dominate.

One technique to deal with this is to design the CCD sensor with a number of read-out ports. The pixel frequency is reduced by a factor equal to the number of ports, leading to a reduction in the read-out noise. Marconi Applied Technologies (as EEV Ltd.) first demonstrated a camera of this type several years ago, and one with 16 ports has recently been developed. However, for a TV type CCD having a practical number of ports, the noise is still typically in the range 5-10 electrons and the low light level performance is not as good as that from an ICCD.

An additional limitation of this method of operation is that several video channels must be processed in parallel and the image has to be re-constituted from the individual segments. Gain and offset variations from one segment to another can result in a patchwork quilt effect, which is further aggravated by the fact that such variations are often temperature dependent. In some applications of target acquisition and tracking the time taken to re-constitute the image (transport lag) can have an adverse effect upon the tracking performance.

2.3 Intensified CCD imaging [ICCD]

At TV rates, the conventional way to image at low light levels is to amplify the signal before the noise from the CCD sensor is introduced. This is accomplished using an intensifier, which is generally fibre-optically coupled to the CCD using optical cement.

Although the sensitivity and resolution performance of both second and third generation intensifiers have improved significantly over the last few years, the intensified CCD solution to low light level imaging has several disadvantages:

1. The poor gain statistics of the micro-channel plate (MCP) results in the introduction of a noise factor between 2 and 3.5.

2. A total of three conversions are necessary from photon to electron to photon to electron, each of which reduces the overall fixed pattern SNR performance.

3. The combination of the proximity focussed gaps and the micro-channel plate within the intensifier adversely affects the system Modulation Transfer Function (MTF), reducing the average contrast in the resulting image.

4. Electron reflections inside the intensifier give rise to halos around any bright points of light in the image, severely reducing the ability to see adjacent detail.

5. At the high gains used at low light levels, ion and X-ray events within the intensifier give rise to small bursts of light, or scintillations, over the picture area, which can become tiresome, particularly over long periods of time.

6. Image intensifiers can be damaged by high light overloads resulting in an image of the highlight being ‘burnt’ into the device due to reduced gain.

7. Image intensifiers are ‘lifed’ items, their performance deteriorating with use due to ion bombardment damage to the photocathode and micro-channel plate.

   The rate at which this degradation occurs is predominantly a function of the faceplate illumination (and temperature). Prolonged use at 0.1 mlux faceplate illumination with brief excursions to higher levels can often result in a reduction of luminous gain to between 50% and 60% of the initially measured value at the ‘end-of-life’ period of operation.

8. Most intensifiers introduce a certain amount of shading into the image due to variations in photocathode sensitivity and micro-channel-plate gain.

9. Intensifiers exhibit significant (Phosphor) lag, which improves signal to noise at the expense of dynamic resolution.

2.4 Electron-Bombarded CCDs [EBCCDs]

In an electron-bombarded CCD, the silicon sensor is back-thinned, suitably processed to be vacuum-compatible and incorporated into the vacuum envelope of the tube. Photoelectrons emitted from the photo-cathode are accelerated directly into the pixels of the CCD by an accelerating voltage, such that for every 3.7eV of input energy, an electron-hole pair is created in the pixel.

The gain statistics of the bombardment process are extremely good and the resulting noise factor is only fractionally above unity. The micro-channel-plate and the phosphor screen are both dispensed with, leading to improvements in MTF and Signal to Noise ratio and their removal also removes the two greatest sources of ions in the vacuum envelope leading to an improvement in scintillation performance and life.

Proximity focussed versions of the EBCCD will exhibit a halo around bright objects in the scene, due to electron reflections.

Marconi Applied Technologies (as EEV Ltd.) was involved in the development of this type of detector in collaboration with Intevac Inc and Charles Stark Draper Laboratory in the USA. The performance of these devices was reviewed in a paper presented at the SPIE International Symposium on Optical Science, Engineering and Instrumentation at San Diego in July 1998.

2.5 The new CCD Technology from Marconi Applied Technologies

2.5.1 General

Marconi Applied Technologies have developed a new CCD camera using an innovative silicon CCD sensor having an Advanced Readout Technology architecture, which effectively reduces the read-out noise. The detector, is the first to provide images of low light level scenes at normal TV rates without the need of an image intensifier.

The technology also allows the user to benefit from the much higher photon quantum efficiency of silicon, compared with the best Gallium Arsenide photocathodes used in the latest intensifiers. By removing the intensifier altogether, significant additional advantages, such as a much improved MTF and the elimination of both halo and scintillations become available.

Unlike intensified systems, the new sensor is solid state, is not damaged by overexposure and is not a ‘lifed’ component, leading to a reduction in total life-cycle costs to the end-user when compared with intensifier-based systems.

A nominally 1" format, 625-line image sensor has been fabricated with 576 pixels per line. The device uses advanced inverted-mode operation (multi-phase-pinned) to reduce dark current noise, and shielded anti-looming technology in order to minimise the signal electron losses to the anti-blooming drains. A further reduction in dark current, dark- current shot noise and dark-current non-uniformity (FPN) has been achieved using a Peltier cooler.

Although the devices to date have all been front-illuminated, development of a back-illuminated version is in progress. Such a device will increase the quantum efficiency of the device and lead to a potential improvement in Signal to Noise level of about 3dB compared to a standard front-illuminated sensor.

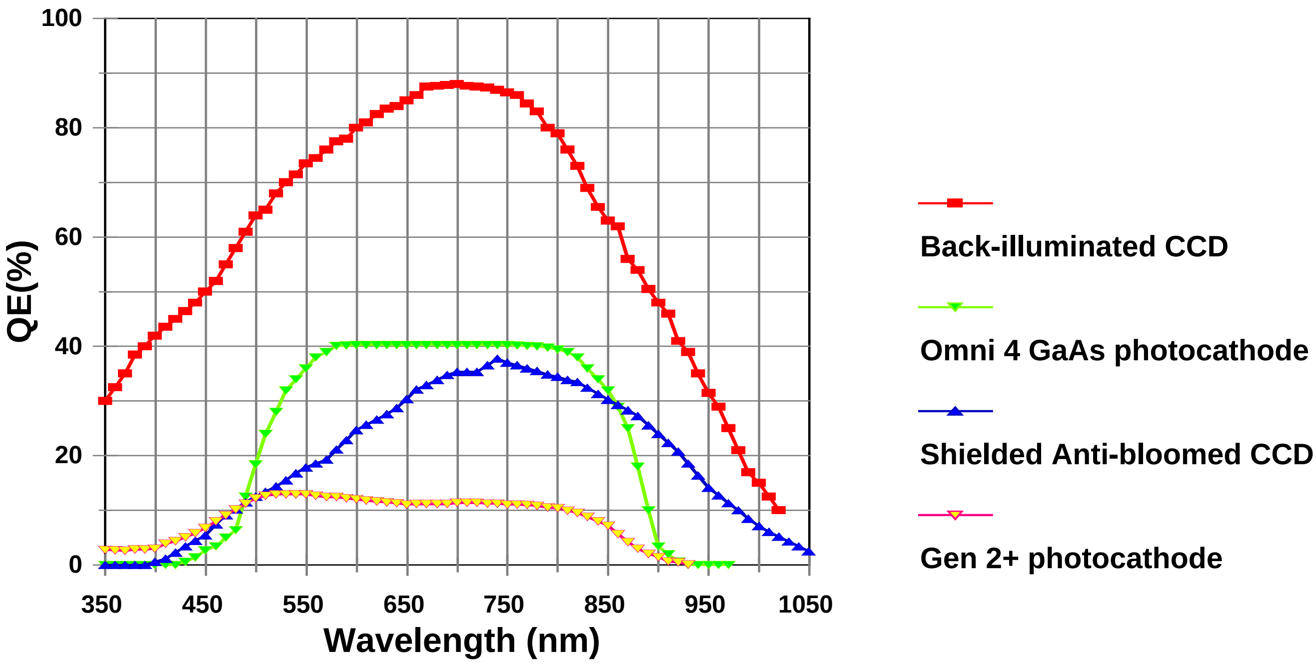
2.5.2 Sensitivity

Figure 2 shows the spectral response of several detectors from which two points are worth noting:-

a. Firstly, it is clear that the back-illuminated CCDs with a peak quantum efficiency of 90% are very much more sensitive than any of the photocathodes currently used in image intensifiers.

Quantum Efficiencies - various sensors

Figure 2



b. Secondly, whereas a multi-alkali or Gallium Arsenide photocathode is practically insensitive to photons having a wavelength longer than 900nm, the silicon sensor has a considerable response to beyond 1 micron. This means that significantly more of the night-sky photons are detected by a silicon CCD.

Figure 3 shows the Irradiance per lux for a tungsten lamp at 2856 K, moonlight and starlight together with the photopic curve:-

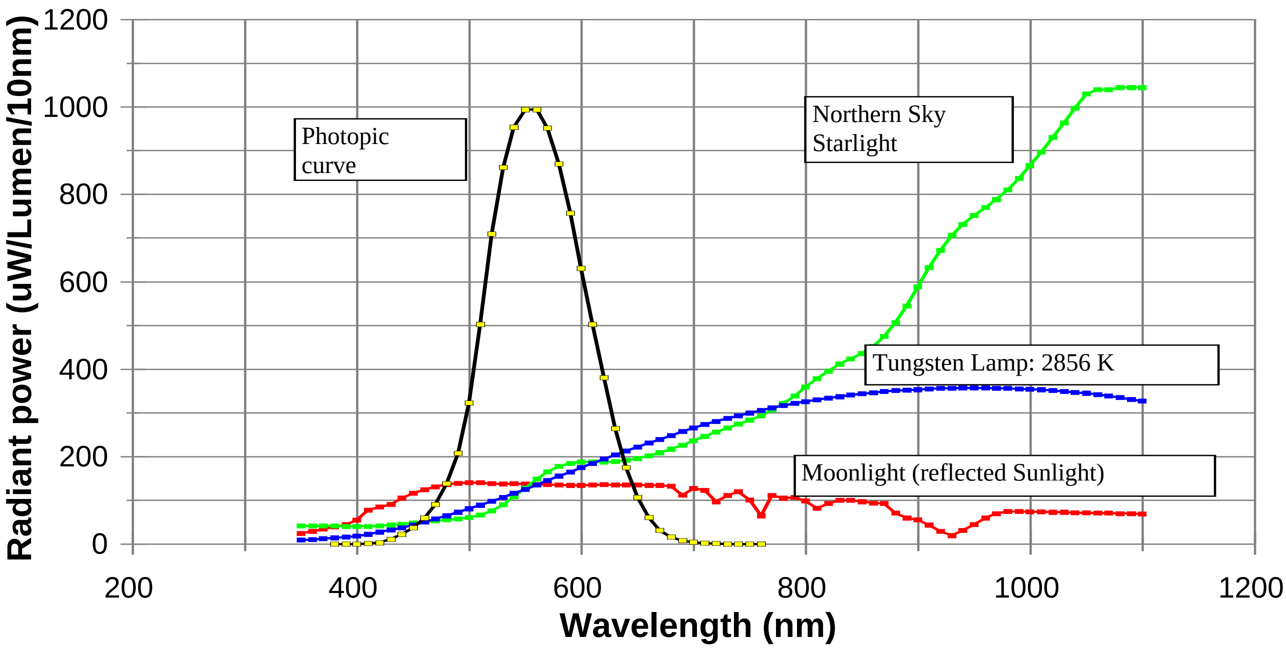
a. The benefit of having a high detector sensitivity out to beyond 1 micron is clear from the curve of Night Sky Irradiance, which shows the rapid increase in the number of photons above 800nm. A Front-illuminated CCD takes advantage of this fact.

b. Tungsten lamps have been used for night vision photometry for many years, as the match with starlight is very good to around 800nm. However, for wavelengths out to 1050nm the discrepancy becomes quite marked, resulting in pessimistic photometric data when compared with natural starlight. This is particularly relevant for front-illuminated devices.

c. An electro-optical system will only benefit from the extra red sensitivity of silicon if the optics are appropriately coated and corrected for aberrations.

Irradiance/lux from several sources

Figure 3

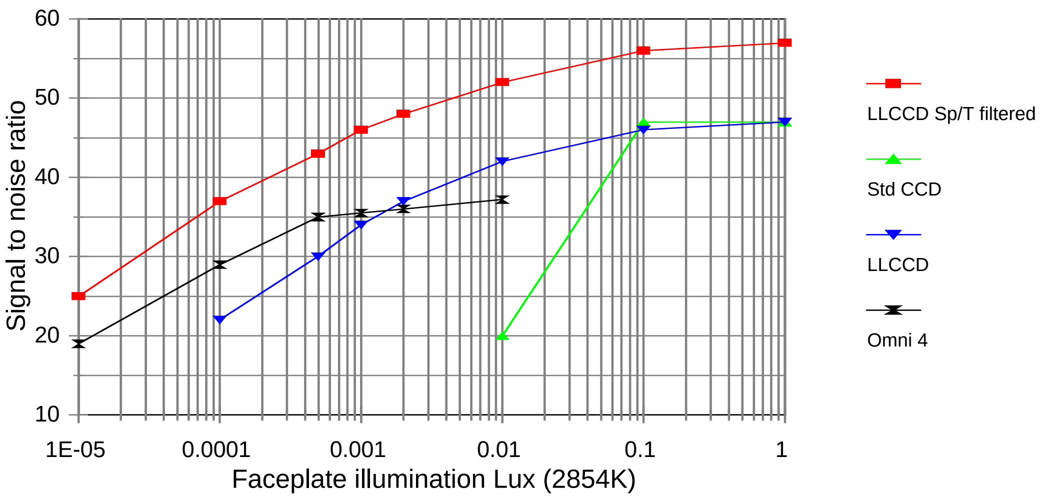


2.5.3 Noise

Figure 4 shows several graphs of Signal to Noise ratio [SNR] against faceplate illumination level.
The figure shows clearly why conventional CCDs cannot be used for low light level imaging as the SNR reduces rapidly with decreasing illumination due predominantly to the effects of read-out noise.
The intensified CCD overcomes this limitation by amplifying the signal before the read-out noise is introduced, resulting in a much improved SNR at low light levels. The SNR at high illuminations, however, is significantly worse by comparison due to gain non-uniformities.
The unfiltered LLCCD appears subjectively superior to the ICCD at all light levels even though (below 1 mL Fig.4) measurements imply otherwise. Fine grain LLCCD “white” noise is less objectionable than ICCD coarse grain “quasi-pink” noise with its objectionable scintillation effects.
A test Spatial/Temporal filter was applied to the LLCCD to mimic the MTF and lag features of the ICCD. Objective and subjective results confirmed that the noise bandwidths for each of the tubes sampling axes (X, Y, T) were between a half and a third of the nyquist bandwidths. ICCD cameras thus enjoy 10-15dbs of noise reduction depending on tube type (Omni- 3/4) and illumination (lag deteriorates at low light levels).
SNR measurements of the LLCCD, with equal noise bandwidths to that of the ICCD, confirm the earlier analysis of sensitivity.
Further detailed noise measurements on the LLCCD sensor revealed the camera noise floor. Readout noise was less than one electron (rms) and thermal noise (-20^{o}C) was one electron (rms). The SNR graph (Fig.4) also confirms this, as the slope is quantum noise limited (10db/decade).

SNR Vs Illumination (Measured)

Figure 4.



2.5.4 Modulation Transfer Function and Resolution

Figure 5 shows the MTFs of an Omni 4 intensified CCD camera and the new solid state camera. The figure clearly demonstrates the significant improvement in contrast that can be gained by removing the image intensifier and using the solid state CCD as the primary detector.

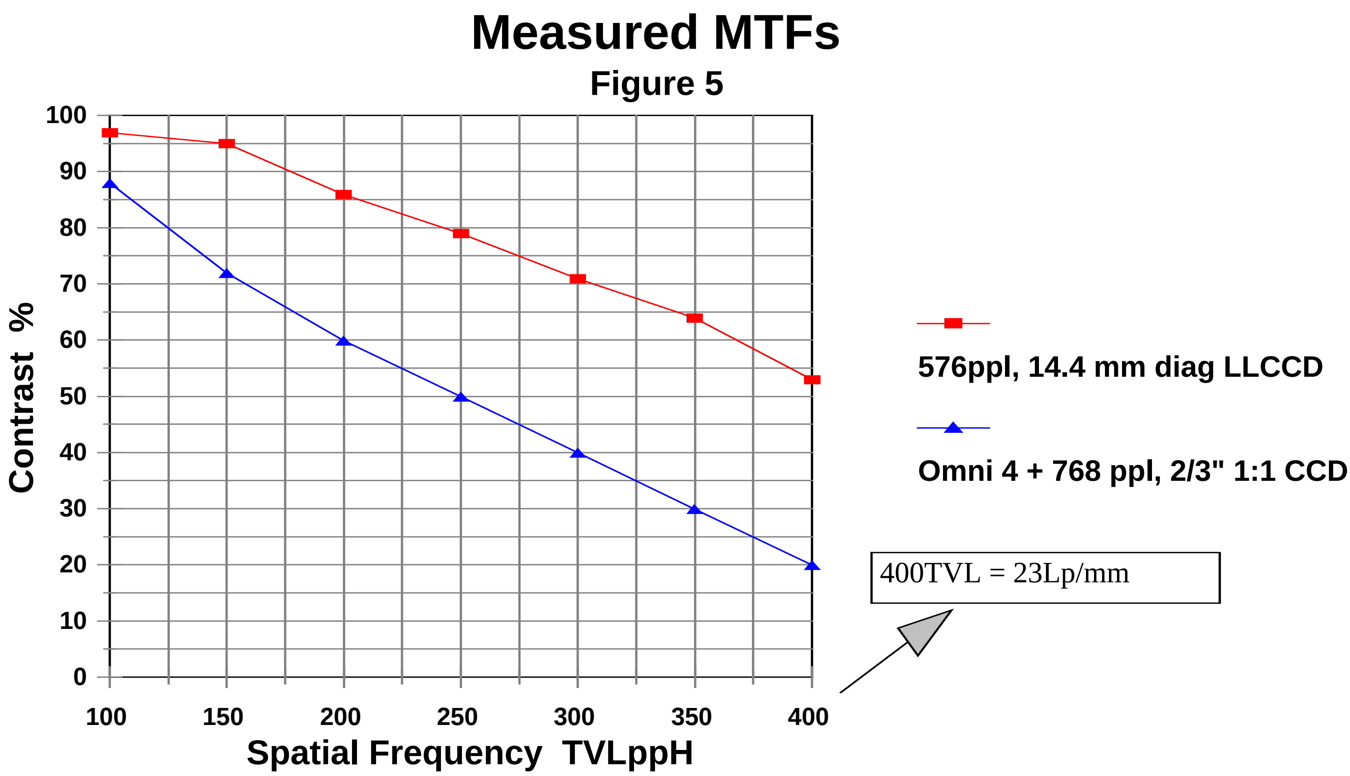
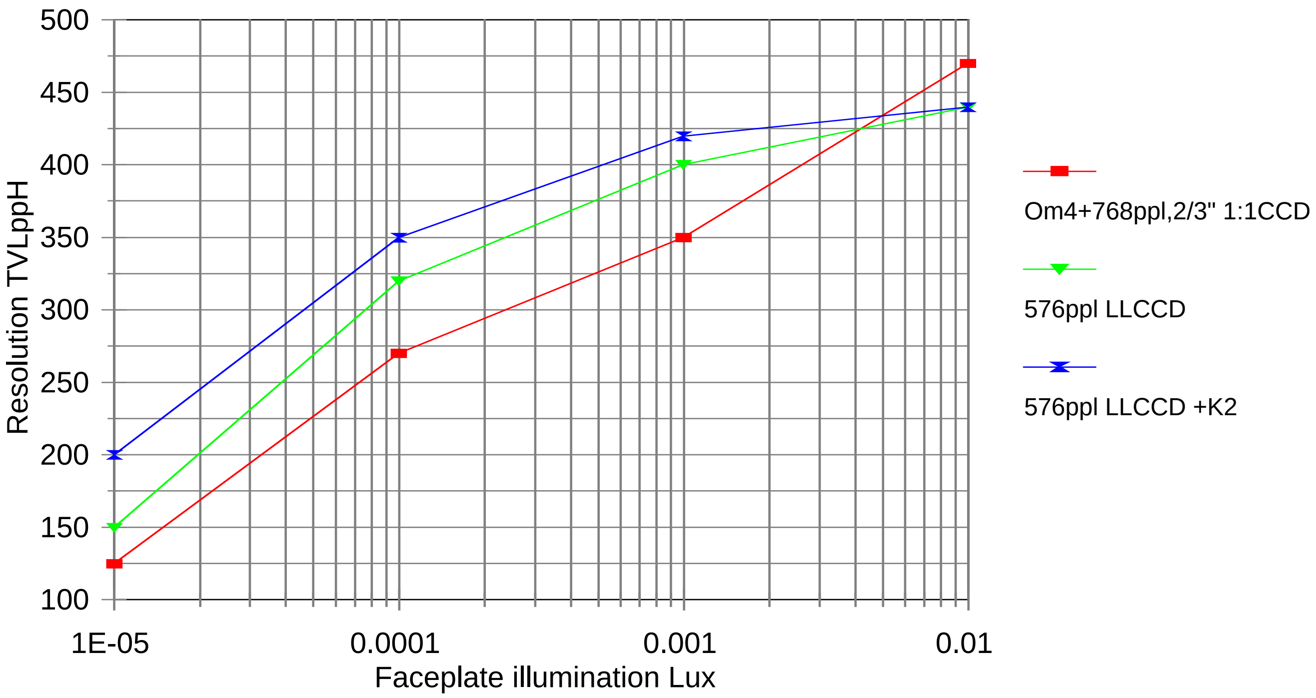


Figure 6 shows the measured results of limiting resolution against faceplate illumination for an Omni 4 intensified CCD camera coupled to a 768 pixel per line sensor, and a prototype LLCCD camera, using a 100% contrast USAF pattern. The figure shows that even without temporal or spatial filtering the performance in terms of limiting resolution of the LLCCD is superior to that of the intensified CCD at low illuminations.

The addition of field recursive averaging (in which ½ the value of the current field is added to 1/4 of the previous field and an 1/8 of the previous but one field etc - i.e. K2) simulates the effect of the phosphor decay time and increases the perceived resolution at low illuminations.

Limiting resolution Vs Illumination

Figure 6. inc f/1.4 lens



2.5.5 Halo and Scintillations

The new CCD camera is totally solid state, which means that it does not suffer from the free-electron and ion induced phenomena such as halo and scintillations.

2.5.6 Frame-Shift Smear

During the frame transfer period, spatial information in the form of pixellated charge in the image area of the sensor is moved quickly into the storage area to be subsequently read-out via the read-out register. A bright object in the field will continue to add charge to each column pixel as it passes by, resulting in a bright vertical smear.

This problem can be overcome by switching an optical shutter during frame-transfer. The transmission of the shutter in the ‘open’ state can be as high as 95% and so very little loss is introduced in terms of sensitivity and SNR.

2.5.7 Life

The new CCD is a solid state device and is not a ‘Lifed’ item
Unlike an image intensifier, the Signal to Noise performance of the new CCD is not subject to the effects of ion bombardment.

2.5.8 Digital Signal Processing (DSP)

The "white noise" nature of the noise of the LLCCD suggests that image processing techniques will improve the SNR and limiting resolution. The results of the spatial/temporal (digital) filter confirm improved resolution with or without lag according to the options chosen.

2.5.9 Other benefits

a. Whilst image intensifiers can be damaged by over-exposure leading to image burn-in, the Low Light CCD is immune to excessive illuminations.

b. The Low Light CCD has a low lag performance by virtue of the fact that no phosphor screen is used. This will manifest itself as better dynamic resolution. Alternatively electronic lag can be added if required for improved SNR at low illuminations.

c. The image quality of the Low Light CCD is good, there being no shading problems (associated with the photocathode and MCP in an intensifier) or fixed pattern noise resulting from fibre-optics (either straight or tapered). Fixed pattern defects have not been evident on the LLCCD at any light level.

3. Current Status

A front-illuminated, 576 pixel per line, 14.4 mm image diagonal, 625 line sensor having a pixel size of 20 x 30 microns with Inverted Mode Operation and Shielded Anti-blooming has been assembled into a number of cameras and has undergone trials and characterisation.

Future devices having 768 pixels per line are planned.

4. Conclusion

Marconi Applied Technologies have produced a new camera which challenges the low light level TV imaging applications previously dominated by vacuum devices. The critical technology includes a new CCD architecture (ART) which delivers video signals from a single output port without the need of an image intensifier.

It is anticipated that future back-illuminated devices will have a superior performance to the present LLCCD.

S.H. Spencer 10th February 2000

Footnote:
This paper is a Revised Version of an earlier publication by J.A.Cochrane/S.H. Spencer presented at the Night Vision Conference (Orlando) 1999.