

# Image intensifier tube performance is what matters

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## ABSTRACT

Image Intensifiers are used in a wide range of applications including observation, industrial instrumentation, analytical instrumentation and scientific research. Characterisation of image intensifier tubes by means of Generation designation provides only information about the tube configuration and does not tell anything about its actual performance. In this paper we will describe which parameters determine the performance of Image Intensifiers and ICCD's and how these behave under different circumstances. Performance data will be given for a number of DEP tubes.

**Key words:** Image Intensifiers, Intensified CCD's, XD-4<sup>TM</sup>, SHD-3<sup>TM</sup>, Gen III, OMNI IV, signal to noise ratio, limiting resolution.

## 1. INTRODUCTION

The way an image intensifier tube performs depends first of all on the scenery observed:

- how much light is there?
- how much contrast has the scene?
- how much dynamics is there in the scene?
- what are the spectral characteristics of illumination and scenery reflection?

Subsequently the quality of the image is determined by how these external conditions are handled by the tube. Different tube types treat these conditions in different ways. The best tube at low light-levels is not necessarily the best choice at the higher light-levels. Because of differences in spectral behaviour it can also be that a specific tube type is superior for observation on the land but not in a forest. Ultimately, a decision on which tube type to use has to be made on the basis of probability of occurrence of these specific conditions.

The best way of course to evaluate an Image Intensifier or ICCD is a field test but before such a test can be done users like to have available test data from which they can judge which tube type is best suited for their application. Type designations or Generation numbers (e.g., Gen II, Super Gen, Gen III, SHD-3 and XD-4) have been reserved for major technological changes [1,2] but don't give any information about the actual performance. Usually the following parameters are used to describe the image intensifier tube performance:

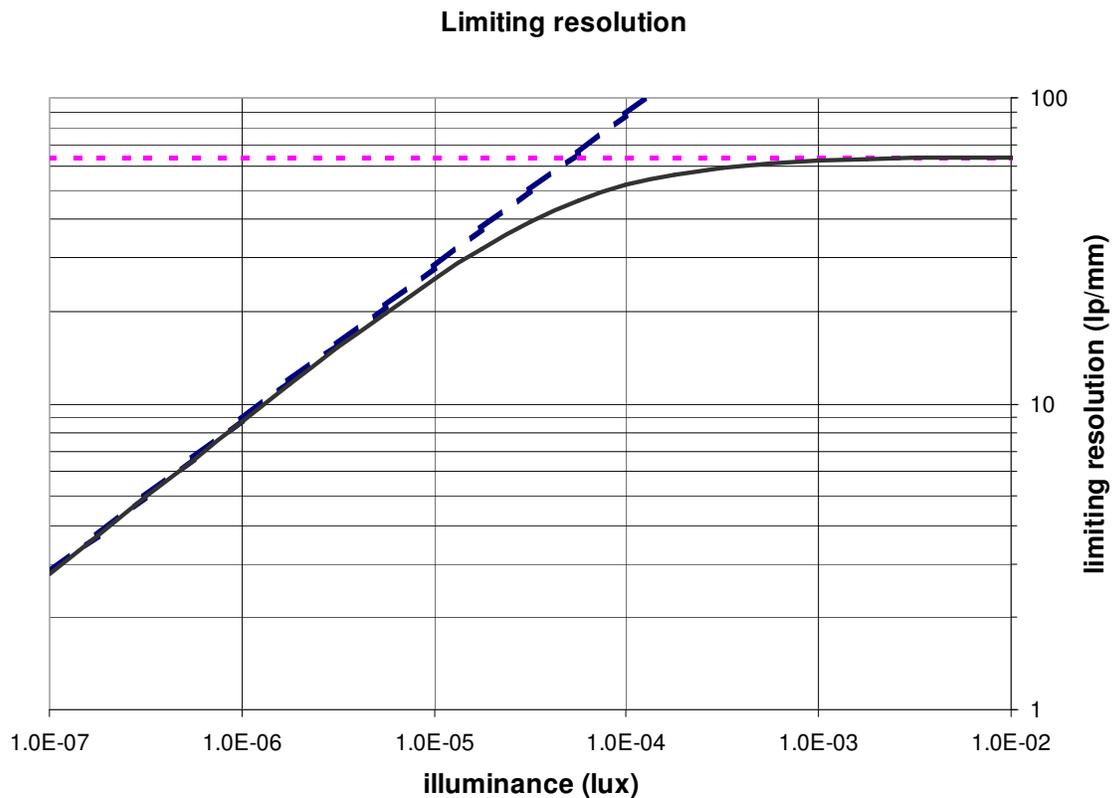
- the signal to noise ratio (SNR)
- the limiting resolution (lp/mm)
- the photocathode sensitivity ( $\mu\text{A}/\text{lm}$ )
- the gain ( $\text{cd}/\text{m}^2/\text{lx}$  or  $\text{fL}/\text{fc}$ )
- the maximum output brightness ( $\text{cd}/\text{m}^2$  or  $\text{fL}$ )
- the equivalent background illumination (EBI,  $\mu\text{lux}$ ).

Not all of these parameters are needed to describe the final performance of the tube; the performance that the user will see. This paper will deal with the parameters mentioned and discuss the consequences for the ultimate target: the field performance. This will be done both for image intensifier tubes and ICCD's.

## 2. THE TWO PERFORMANCE REGIMES

An image intensifier tube amplifies light. If there is no light, there will be no image and the observer will only see the effect of the dark noise. If there is only little light there won't be a continuous illumination but a "hail like" bombardment by single photons. Originally, at the very low illumination levels, there are not enough photons to form an image for the observer. With increasing illumination the number of photons increases and at first a noisy image shows up. With such a noisy image it is not possible to resolve small image details. When the light-level is further increased the resolution increases and smaller image details start to show up depending on the light-level. This regime in which the observation of image details is obscured by noise is called the "Photon Counting Limit" or "Low Light-Level Limit". In this regime the quality of the picture depends on the light-level.

If there is enough light the noisiness will disappear. The quality of the picture is then much higher and determined by the parameters of sharpness and contrast. It will not depend on the illumination intensity. This light-level regime is called the "Photon Noise Limit" or "High Light-Level Range". Fig. 1 shows the two performance regimes.



**Fig. 1** The limiting resolution as a function of illuminance showing the high and low light level regimes

## 2.1 The Photon Counting Limit

In the low light-level regime the information density is determined by the light-level. This effect is illustrated in Fig. 2. At very low light-levels no structures are visible at all. The image consists of a number of light speckles but the observing element behind the tube cannot make a picture from it. At higher light-levels the number of photons increases resulting in a higher density of image speckles. First the larger image details become visible (20 lp/mm target) whereas the smaller image details are still hidden in the noise. At even higher light-levels these small image details such as the 60 lp/mm target in Fig. 2 become visible too. How well the image details become visible at the output of the tube depends on its quality, mainly on its signal to noise ratio but also on its resolution.

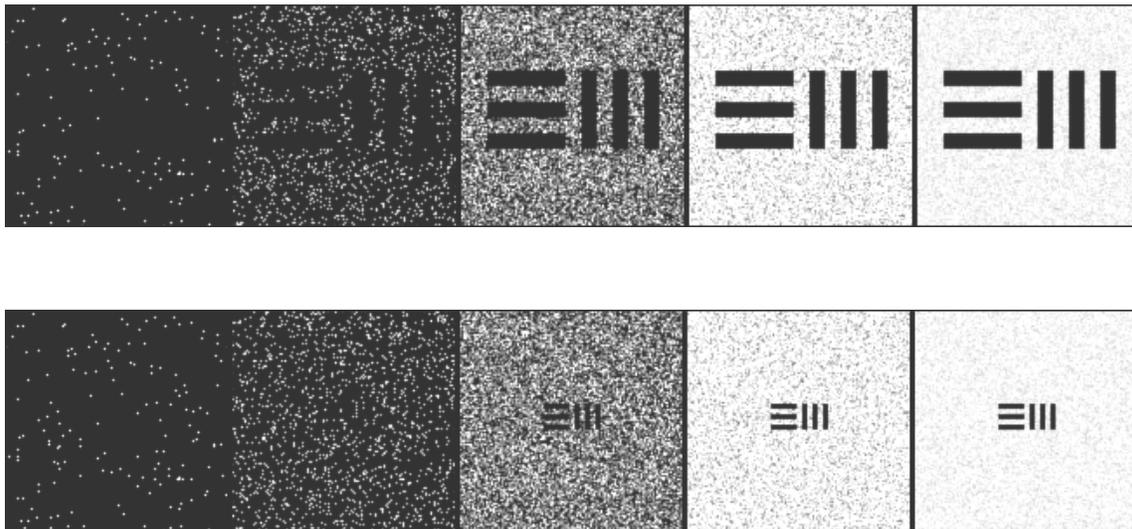
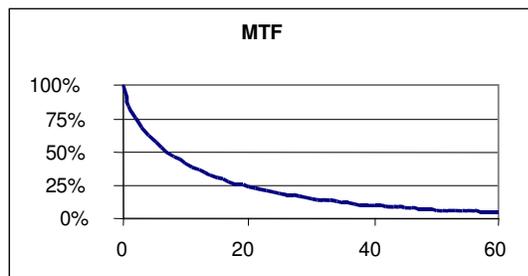
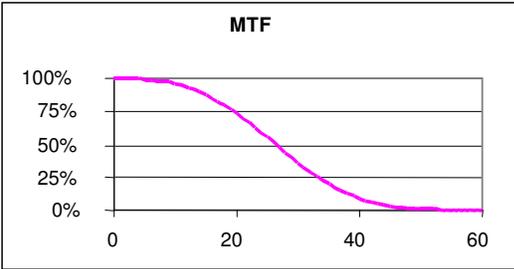


Fig. 2 The 20 lp/mm and 60 lp/mm targets at different light levels.

## 2.2 The Photon Noise Limit

From a certain light-level onwards the image quality is no longer determined by the input light-level but by the image transfer characteristics of the Image Intensifier. How the contrast of a scene is transferred by the tube is expressed by the Modulation Transfer Function (MTF) parameter. The MTF of an imaging system gives the contrast at the output when a 100 % modulation at the input is applied. This contrast at the output is a function of the spatial frequency (lp/mm). From the MTF curve the limiting resolution can be derived. The limiting resolution is closely related to the contrast at high line pairs per mm. It coincides with the spatial resolution point at which the MTF is in the range of 3 to 5 % depending on the way of measurement. Fig. 3 shows how important a good MTF at the low spatial frequencies is for the image quality. A good contrast at low line pairs gives a "clear" image as shown by the left top part of the image of Fig. 3. A low MTF value gives a "hazy" impression, see the right bottom part of the image in Fig. 3. Please note that despite the bad contrast at low line pairs, the limiting resolution is very high in the latter part of the image.



**Fig. 3** The picture shows the consequences of MTF.

### 3. PERFORMANCE PARAMETERS OF IMAGE INTENSIFIERS AND ICCD'S

#### 3.1 Signal to Noise Ratio

The SNR is defined as the Image Intensifier output brightness divided by the root mean square of the variations in output brightness and is usually measured with white light at a light-level of  $108 \mu\text{x}$ . The SNR is proportional to the square root of both the area of interest and the applicable bandwidth of the observing element. A circular reference area with a diameter of 0.2 mm is chosen. The bandwidth is in accordance with the storage time in the human eyes and amounts to 10 Hz.

A number of tube factors play a role in the SNR performance of an Image Intensifier:

- First of all the photocathode sensitivity because not every incoming photon is transferred into an electron. The Quantum Efficiency (QE) of photocathodes depends on the wavelength and can reach the 30 % range. A photon that is not transferred into an electron does not contribute to the image, thus increases the noisiness.
- The loss of photo-electrons between photocathode and MCP. Emitted photo-electrons get trapped by the MCP and hence won't be amplified and add to the noisiness of the image. The degree of trapping depends on the specific tube structure. As shown in Fig. 4, specifically the ion barrier film on top of the MCP in third generation tubes, needed to protect the GaAs photocathode, is a photo-electron killer. That many photo-electrons get trapped in the MCP-film in Generation III tubes that the DEP XD-4 tubes obtain the same SNR notwithstanding the lower photocathode sensitivity. For state-of-the-art Image Intensifiers used for Night Vision nowadays an SNR of 24 is obtained.
- The statistics of the MCP
- The statistics of the phosphor screen. The effect of the MCP and the phosphor screen on the SNR translate into a total noise factor F, see Eq. (1).

An important conclusion that can be drawn from Fig. 4 is that the type of tube is not a performance indicator and that also a higher photocathode sensitivity does not guarantee a better performance. What matters with respect to performance is the SNR of the complete image intensifier tube and **not** tube type designations like Gen II, Gen III or Gen IV or even **not** absolute photocathode sensitivity figures.

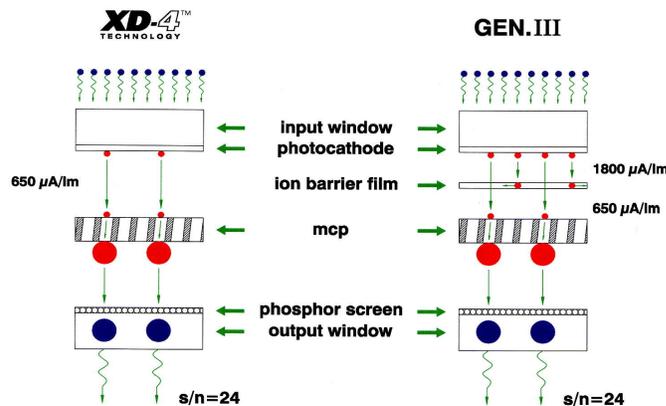


Fig. 4 Visualisation of the difference between XD-4 and Gen III

### Spectral behaviour

How well one can see with Image Intensifiers is not only determined by their sensitivity and the illumination circumstances but also by the reflective characteristics of the materials constituting a scene. In environments such as the desert, barren and rocky land and coastal areas the relevant reflectivity variations at night lie in the blue/green part of the spectrum whereas forest spectral information is in the (near-infra) red. For other applications than Night Vision and Surveillance the scene information can be anywhere in the spectrum running from the UV to the NIR including solely in the UV or blue/green. For characterising the performance of tubes for scenes with different spectral distributions the spectral SNR is a useful tool.

In contrast to the white light SNR the spectral SNR is not measured in practice. For tube evaluation purposes one can calculate the spectral SNR by taking the photocathode response (QE) and scaling it to the measured white light SNR. This can be done by applying a spectral weight factor derived from the spectral radiation of the 2850K lamp. Fig. 5 shows a comparison between the scaled spectral SNR of a Gen III tube and the DEP XD-4 tube, both having a white light SNR of 24. The plot shows a slight advantage for the Gen III photocathode in the infrared region and a clear advantage for the DEP XD-4 tube in the green/blue region.

### Spectral Signal to Noise Ratio

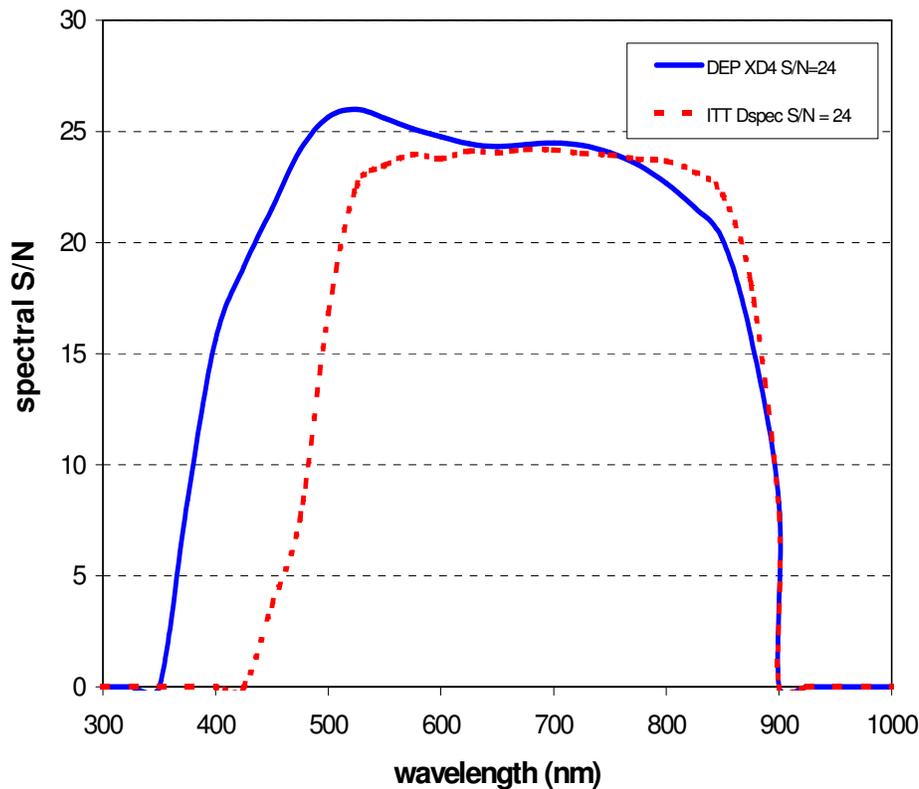
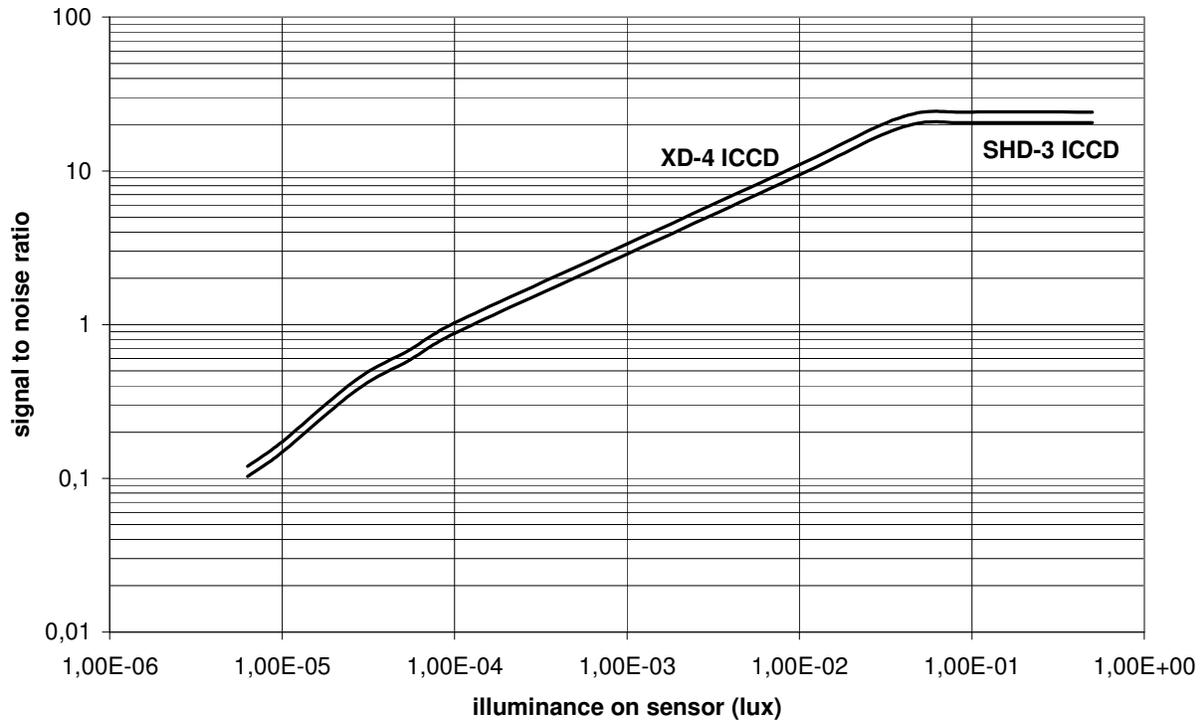


Fig. 5 The spectral signal to noise ratio for XD-4<sup>TM</sup> and Gen III, Omnibus IV/V.

The photocathode determines the spectral sensitivity band of the tube. However, with respect to the low-light-level performance the photocathode is only one part of the chain of components. The spectral SNR is a much better measure for how good the performance of a tube actually is than the spectral photocathode sensitivity.



**Fig. 6 Signal to noise ratio behaviour of XD-4 and SHD-3 based ICCD's of DEP**

For complete Intensified CCD's (ICCD's) the SNR is not measured separately in practice. Only the white light SNR of the tube before CCD-coupling is measured. For evaluation purposes one can calculate the SNR in the photon noise limit of an ICCD with the help of the noise factor determined from the tube white light SNR measurement by means of the following formulae [3]:

$$\text{SNR} = \sqrt{(AEST_i/(eF))} \quad (1)$$

with: E = input illumination (lux),  
A = area of interest (m<sup>2</sup>),  
S = photocathode sensitivity (A/lm),  
t<sub>i</sub> = integration time (s),  
e = elementary charge = 1.6<sup>E</sup>-19 C,  
F = noise factor.

For ICCD's usually a reference area of one CCD-pixel is chosen for the SNR and - when read out at TV-speed - the integration time equals one video frame. Fig. 6 shows the SNR versus input illumination for two types of

ICCD, i.e. one equipped with a DEP XD-4 tube and one with a DEP SHD-3 tube. The SHD-3 tube has a white light SNR of 20 whereas the XD-4 tube has a white light SNR of 24. In the photon noise limit the SNR scales with 5 dB; in the background noise limit ( $10^{-6}$  lux light-level range) with 10 dB and at high light-levels from about 0.1 lux onwards the SNR is constant due to structural noise. At SNR's higher than 1 image details at a pixel level can be resolved. For the XD-4 ICCD of DEP this can already be done around  $10^{-4}$  lux.

### 3.2 MTF and Limiting Resolution

As explained in section 2.2 of this paper, the MTF is the best indicator for field performance in the high light-level regime. However, in general only the limiting resolution is determined in order to describe the high light-level performance of Image Intensifiers. Measuring the limiting resolution is a rather subjective method and is done by reading the maximum spatial frequency on a USAF target that can be resolved by a human observer. Two tube types for which it is concluded that they have the same limiting resolution reading may still have quite a difference in image quality. From Fig. 3 it is obvious that the top-left image is sharper and clearer than the bottom-right image notwithstanding its limiting resolution is lower. Most observers will prefer the top-left image. The explanation for the superior quality of the top-left image is the high MTF at low spatial frequencies. Knowing this, DEP has developed some time ago their XD-4<sup>TM</sup> type of Image Intensifier with a superior MTF as is shown in Fig. 7. The limiting resolutions of the DEP SHD-3<sup>TM</sup> and XD-4<sup>TM</sup> tubes are, respectively, in the range of 50 and 64 lp/mm.

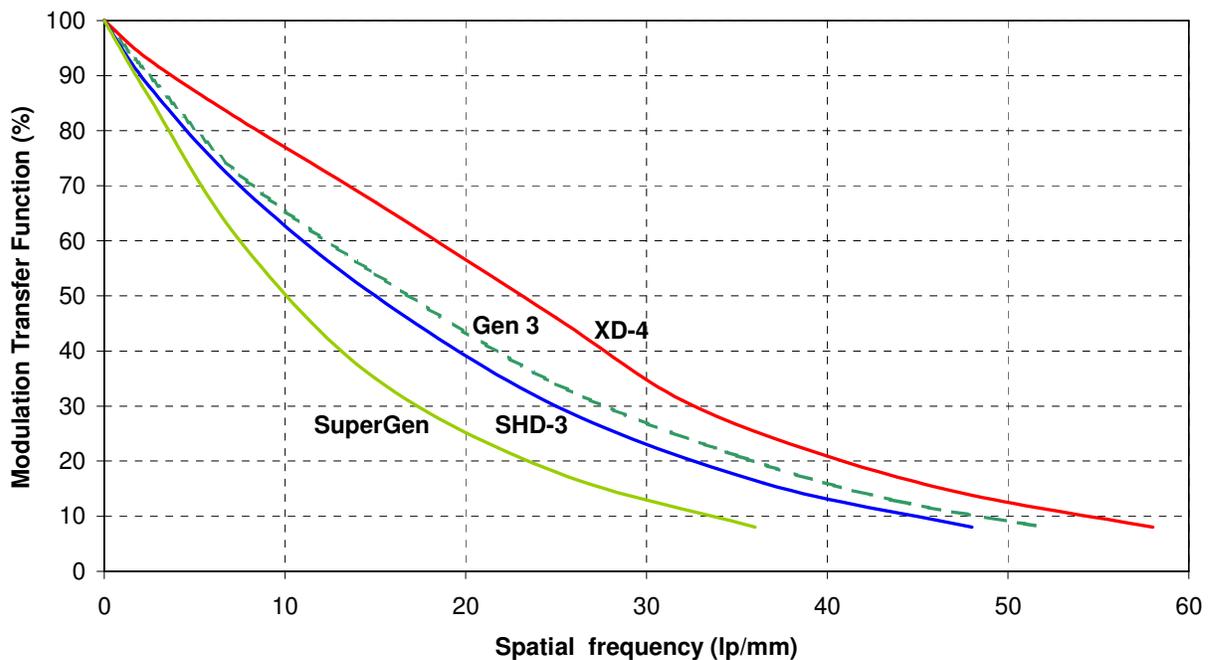


Fig. 7 Modulation Transfer Function of various MCP-based image intensifier tube types.

### Intensified CCD's (ICCD's)

For Image Intensifiers coupled to CCD's by means of tapered fibre-optics the MTF of the total system is given by the product of the MTF's of the individual components. This means that any ICCD type when equipped with the DEP XD-4 Image Intensifier benefits in full from the high MTF of this tube and provides the best image quality. Like for Image Intensifiers, usually only the limiting resolution is measured for ICCD's. The total resolution of any combination of optical components is given by the following formulae:

$$1/(R_{\text{system}})^2 = \sum_{i=1}^n \{1/(M_i R_i)^2\} \quad (2)$$

with:  $R_{\text{system}}$  = total system resolution (lp/mm),  
 $n$  = number of optical components,  
 $M_i$  = integrated magnification until stage  $i$ ,  
 $R_i$  = resolution in lp/mm of stage  $i$ .

From Eq. (2) it can be derived that for the resolution and MTF of an optical system it is advantageous to do any required demagnification as near as possible to the end of the system chain. Further, the smaller the pixels of the CCD the higher the resolution of the ICCD. Table 1 provides the resolutions for a number of XX1700-type of ICCD's of DEP consisting of an 18 mm format Image Intensifier coupled to either a half-inch or 2/3-inch format CCD via a taper with matching demagnification. The resolution of the taper is about 83 lp/mm in all cases.

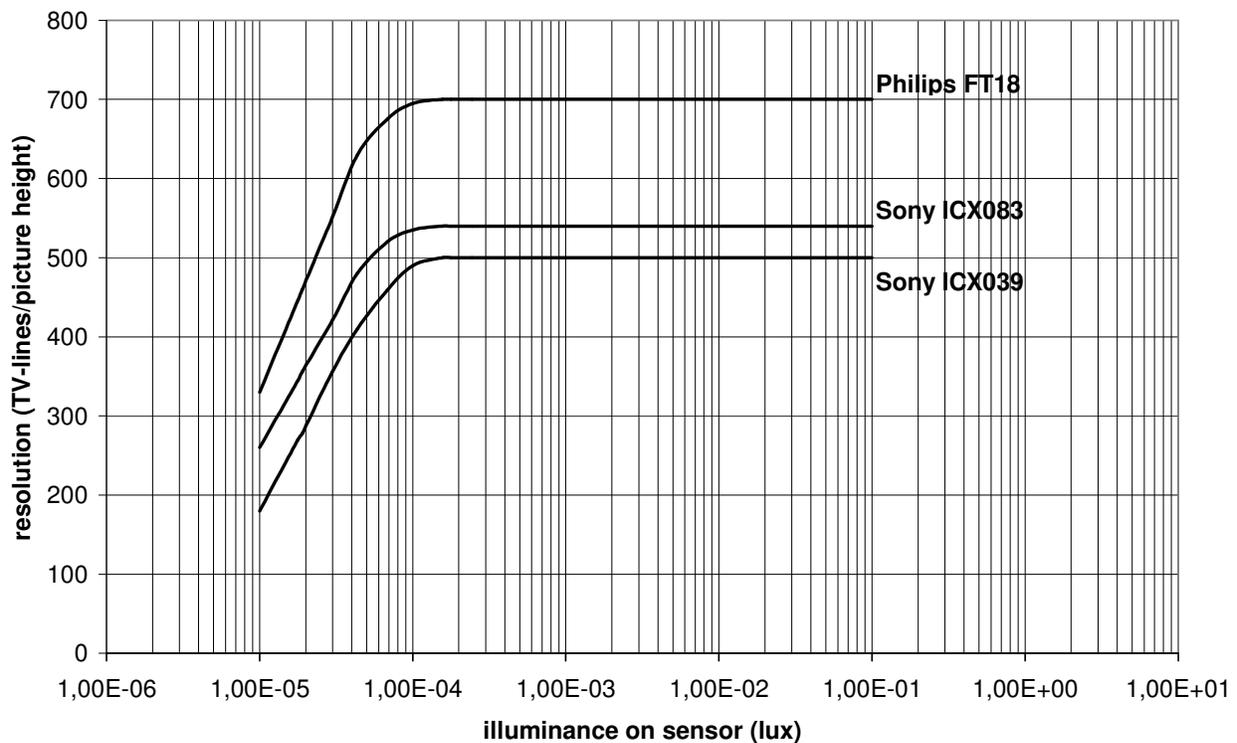


Fig. 8 Resolution behaviour of XD-4 ICCD's for three different types of CCD.

Figs. 8 and 9 show the limiting resolutions as a function of input illumination. Clearly, the noise limit where every extra photo-electron contributes to a better resolving power of image details and the high light-level regime where the MTF governs the image quality can be distinguished. As expected, the XD-4 Image Intensifier coupled to the CCD with the highest resolution gives the best result.

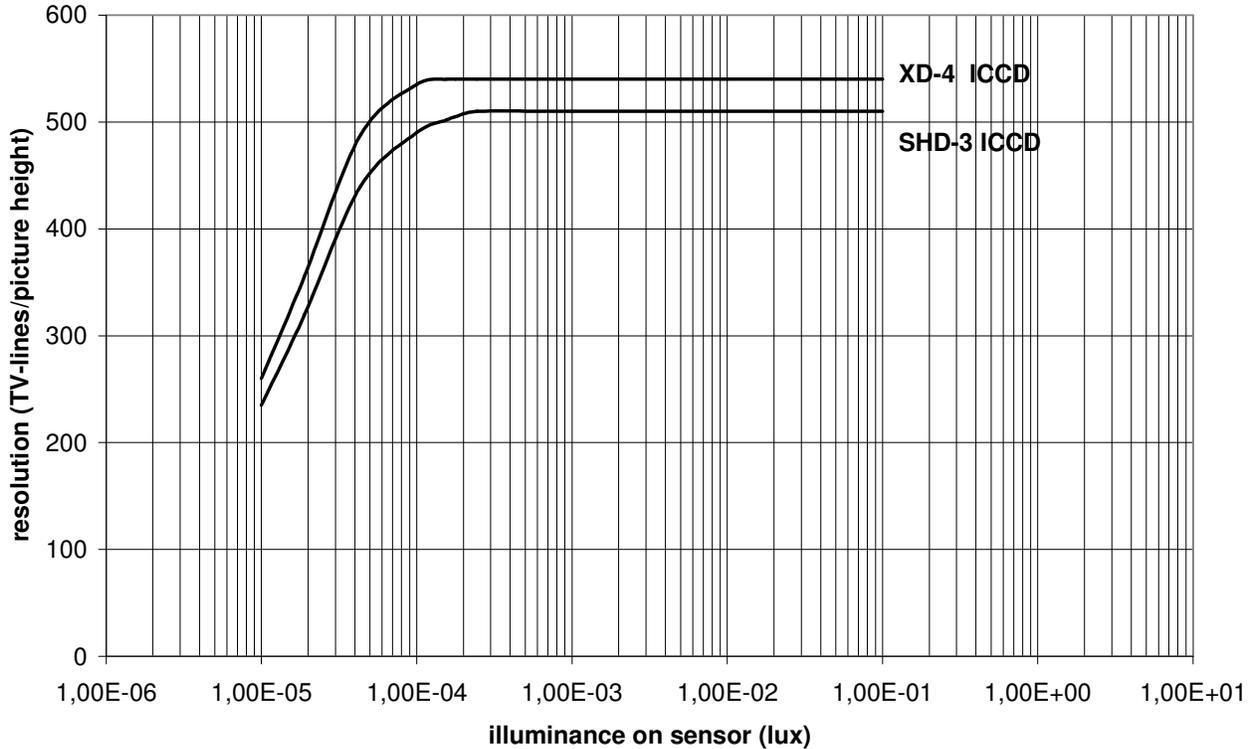


Fig. 9 Limiting resolution of XD-4 and SHD-3 based ICCD's.

Item	Type of Image Intensifier	CCD data				Resolution of ICCD	
		Type	Format	Pixel width	Pixel height	in lp/mm	in TV-lines/picture height
1	XD-4	Philips FT18	2/3-inch	7.5 $\mu\text{m}$	7.5 $\mu\text{m}$	28.9	715
2	XD-4	Sony ICX083	2/3-inch	11.6 $\mu\text{m}$	11.2 $\mu\text{m}$	25.7	540
3	XD-4	Sony ICX039	1/2-inch	8.6 $\mu\text{m}$	8.3 $\mu\text{m}$	23.8	500
4	XD-4	Sony ICX083	2/3-inch	11.6 $\mu\text{m}$	11.2 $\mu\text{m}$	24.2	510

Table 1 Resolution of various types of XX1700 ICCD in the high light-level regime.

### 3.3 Gain

The required gain for an image intensifier system heavily depends on the specific application. For direct view applications the luminance gain expressed in fL/fc is of importance and is in the range of  $3 \times 10^4$  to  $5.5 \times 10^4$  fL/fc for an XD-4 Image Intensifier and  $5.5 \times 10^4$  fL/fc for an Omnibus IV Gen III tube. In the photon counting limit a higher gain does increase the intensity of the event speckles but also does increase the intensity of the noise speckles. The net effect is that the SNR integrated over a large enough area will still go up a bit but the image keeps its noisy appearance because it is built up of discrete events hidden in noise events. Roughly one can say that from a gain of  $3 \times 10^4$  fL/fc onwards the image keeps the same noisy impression for the observer in a direct view application when the gain is increased.

In the high light-level regime the gain has to be reduced referred to its factory preset maximum setting in order to get an optimum performance in the sense that the output intensity is comfortable to the eyes of the observer. This is done via the Automatic Brightness Control (ABC), a feature of the integrated power-supply. The ABC keeps the Image Intensifier output brightness constant from a certain light-level onwards. Depending on the specific system build-up the maximum output brightness (MOB) set by the ABC is in the range of 5 - 15  $\text{cd/m}^2$  which equals 1.6 to 4.8 fL.

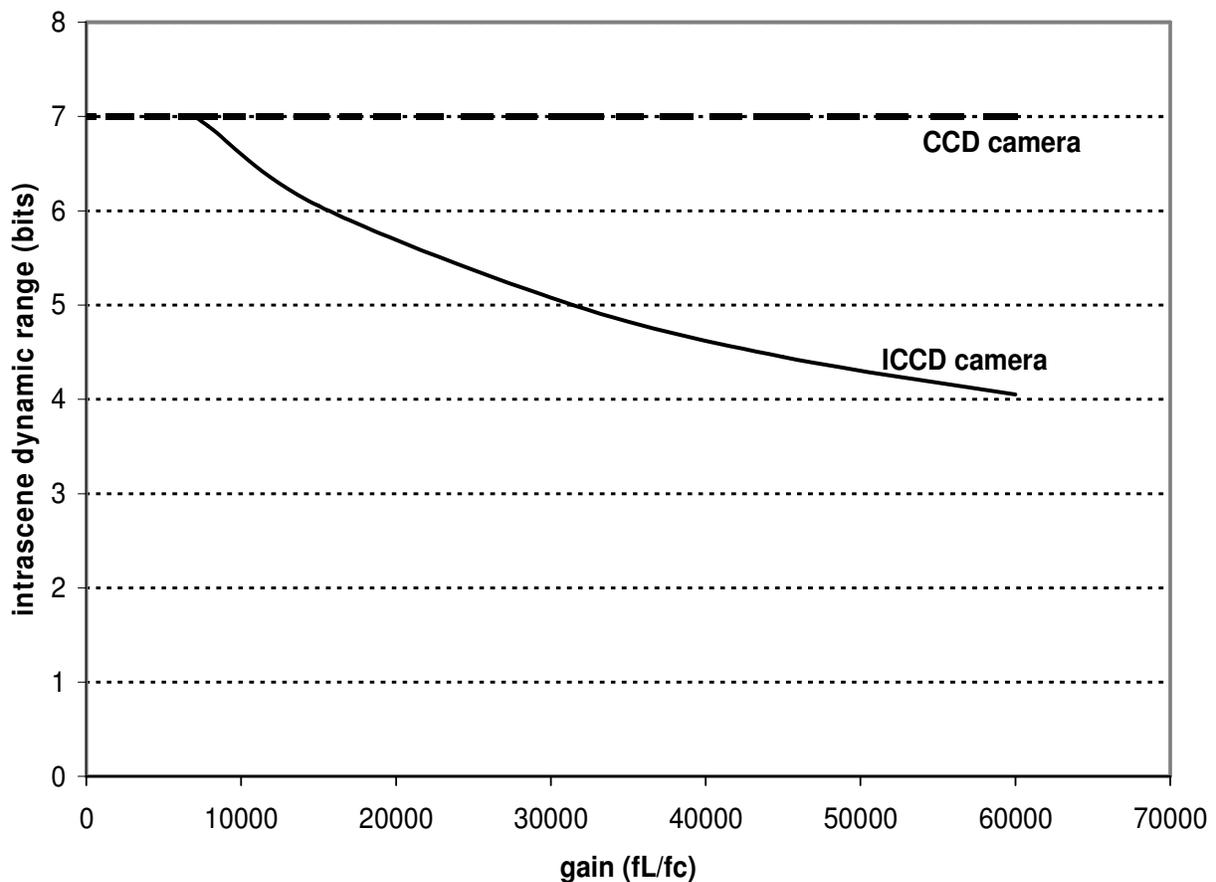


Fig. 10 Intrascene dynamic range of an ICCD as a function of Image Intensifier gain.

For an ICCD connected to a video camera used in a Surveillance application the gain should in fact be expressed in V/lux. However, because of the camera dependence this is usually not done and only the luminance gain of the Image Intensifier is specified. An issue that is often overlooked for ICCD's is the relationship between its intrascene dynamic range (IDR) and the gain of the Image Intensifier [4]. The tube gain determines how many secondary electrons are created in a potential well per created photo-electron. Because of the quantisation of the photo-electrons the potential wells fill in discrete steps. For instance, around 3100 secondary electrons are created per photo-electron for a tube adjusted at a gain of 31400 fL/fc taper-coupled to a Sony 2/3" CCD. Assuming a full well capacity of 100k electrons this means that saturation is obtained after 32 steps and that the IDR amounts to 32 gray values or 5 bits. Lowering the gain makes the quantisation steps smaller and hence improves the IDR. As shown in Fig. 10, the IDR is inversely proportional to the gain until a rather low gain setting where the IDR is determined by the noise floor of the camera. For a standard camera read out at video speed its IDR is only in the range of 7 bits. For special cameras the IDR can be much higher. Surveillance circumstances are dealing with very dynamic scenes. In order to obtain both a good IDR and low light-level performance a gain setting in the range of 22000 fL/fc is recommended for ICCD's.

The MOB for the Image Intensifier part of the ICCD has to be set below the value that leads to saturation of the CCD. For the DEP ICCD's the MOB is set in general in the range of 1 fL (3 cd/m<sup>2</sup>).

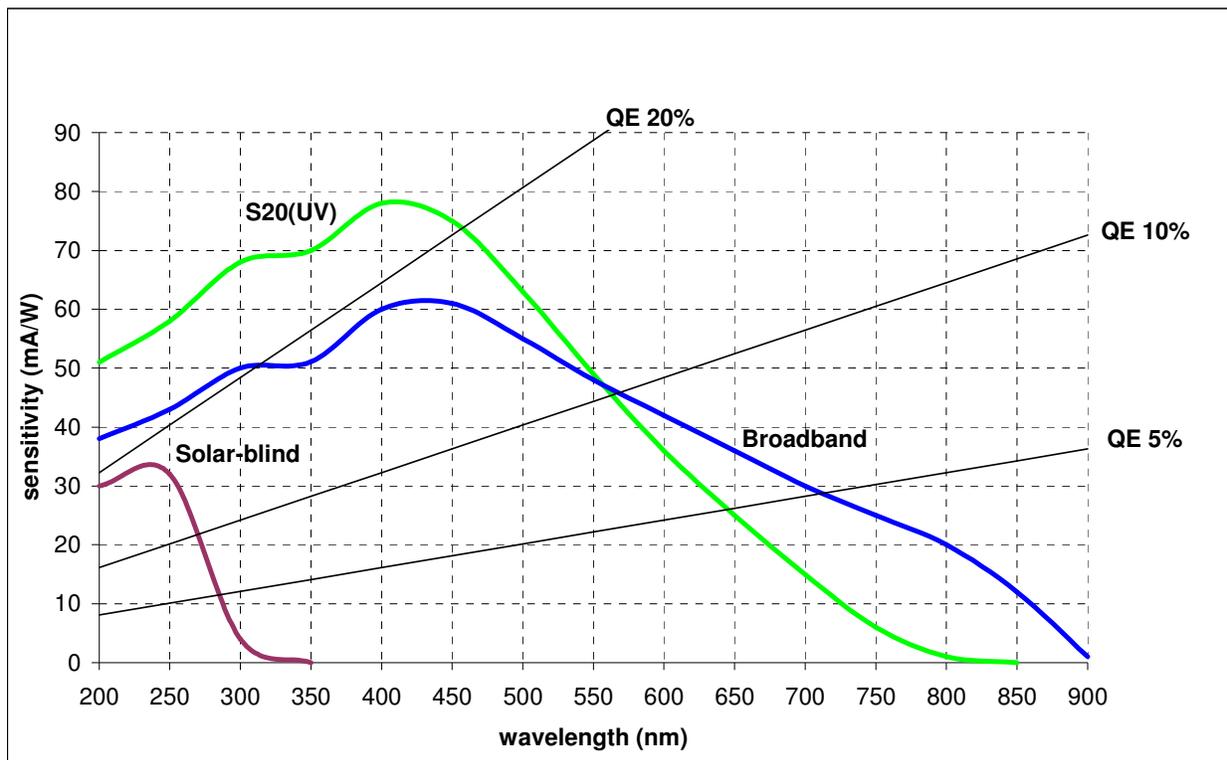


Fig. 11 Some examples of photocathode types different from the traditional Night Vision one.

For Image Intensifiers and ICCD's watching a scene with only a spectral contribution within a specific wavelength band, characterised as the not purely Night Vision application, the tube gain expressed in photons per photon determines the performance rather than the luminance gain expressed in fL/fc. Different types of photocathode compared to the one that is common for Night Vision may be used depending on the wavelength range of interest. The spectral sensitivities of these other types of photocathode are shown in Fig. 11. Table 2 compares the luminance gain and photon gain at 520 nm for an XD-4 tube and a tube with an S20 photocathode, both tubes having the same phosphor. In case we deal with, e.g., a scene with monochromatic radiation of 520 nm, then the S20 tube has a higher photon gain and this is what counts for this application.

Type of tube	Luminance gain (fL/fc)	Photon gain at 520 nm (photons/photon)
XD-4	40000	10700
XX1450, tube with S20 photocathode	16600	14200

**Table 2 Luminance versus photon gain behaviour for two tube types.**

### 3.4 Equivalent Background Illumination (EBI)

The EBI is the background noise of the Image Intensifier and mainly comes from the thermal emission of the photocathode. The EBI adds noise speckles to the image. These noise speckles are only visible in the photon counting light-level range because the tube has a high gain there. The EBI plays no role in the high light-level regime. The EBI is usually expressed in lux and can as such directly be compared to the photocathode illumination from the scene. However, in order to see what happens, it is helpful to express the EBI in number of dark counts per reference area per time unit. This is done in Table 3. E.g., the EBI adds less than 3000 noise events per video frame to the image of an XD-4 based ICCD in the photon counting regime.

Type of tube	EBI in $\mu\text{lx}$	Dark counts (cts/s/cm <sup>2</sup> )	Dark counts per video frame
XD-4	< 0.15	< 50000	< 3000
S20 photocathode	< 0.01	< 1500	< 90
S20UV photocathode	< 0.003	< 150	< 9
Solar Blind	-----	< 5	< 0.3

**Table 3 Typical dark count rate levels at room temperature.**

#### 4. CONCLUSIONS

In order to select the best image intensifier tube for a specific application it is essential to distinguish between the low light-level regime and the high light-level regime. At low light-levels the signal to noise ratio governs the performance. Although important because it is one of the means to achieve a good SNR, the photocathode sensitivity is not a performance determining parameter by itself. A tube with a high photocathode sensitivity but a high noise factor in the rest of the tube may still have a poor SNR. It is not measured yet but in this paper we have shown that the spectral SNR would be a useful tool for selecting the best tube type for a given application. The spectral SNR gives more information than the white light SNR. The type of photocathode does determine the spectral sensitivity band.

In the high light-level regime the limiting resolution is a useful parameter, especially with respect to predicting the image quality of ICCD's, but the MTF is the governing parameter with respect to the performance of Image Intensifiers and ICCD's. The DEP XD-4 tube with its high MTF at low spatial frequencies has shown in field tests that this is a very important feature to get clear and sharp images. The number of pixels of the CCD used has a large impact on the limiting resolution of the complete ICCD. A resolution of 710 TV-lines/picture height is obtained with an XD-4 based ICCD equipped with a 1K x 1K CCD.

We have seen that extremely high gain settings for an Image Intensifier does not mean that the image quality improves in the photon counting limit because the image keeps the same noisy appearance because of the non-continuous illumination. In ICCD applications a high tube gain degrades the intrascene dynamic range.

Field tests have proven that there is a clear balance in performance between the DEP XD-4 tube and the Gen III Omnibus IV and in some respects, especially with respect to uniformity, the XD-4 has some advantages. Having the XD-4, it is the goal of DEP to develop the XD-5<sup>TM</sup> Image Intensifier with a quite higher SNR, an ongoing improvement in MTF and resolution and further improvement in cosmetic quality to achieve full TV-compatibility.

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