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*Title:* Performance of Image Intensifiers in Radiographic Systems

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# Performance of Image Intensifiers in Radiographic Systems

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## ABSTRACT

Electronic CCD cameras equipped with image intensifiers are increasingly being used for radiographic applications. These systems may be used to replace film recording for static imaging, or at other times CCDs coupled with electro-optical shutters may be used for static or dynamic (explosive) radiography. Image intensifiers provide precise shuttering and signal gain. We have developed a set of performance measures to calibrate systems, compare one system to another, and to predict experimental performance. The performance measures discussed in this paper deal with image quality parameters relating to resolution and signal-to-noise ratio.

**Keywords:** Image intensifier, radiography, CCD, camera

## 1. INTRODUCTION

There are many different types of image intensified cameras in use today. Imaging objectives are used to define experimental requirements and desired system performance. Recording specifications may include field of view, resolution, dynamic range, sensitivity, shutter times, and number of images. To aid in the process of identifying and refining requisite system performance characteristics, we have established a set of performance measures that can be used to provide consistent system comparisons along with modeling information. Optimal system performance is dependent on compatible tube selection. This paper investigates the use of various image tubes used in radiographic imaging systems and discusses the relative merits of commercially available planar diode and micro-channel plate (MCP) image intensifiers. Image intensifiers are sometimes used in conjunction with other image tubes such as framing cameras or electrostatic minifiers and some of these combinations are discussed.

## 2. INTENSIFIER PARAMETERS

Image intensifier selection parameters include image tube type, photocathode and phosphor material, input and output window material, resolution, extinction ratio, dynamic range and sensitivity.

### 2.1 Intensifier Type

MCP image intensifiers (MCPII) are used extensively for night vision equipment, which typically employs small (18 mm) diameter tubes. MCPII's are also used in camera systems, sometimes utilizing large diameter MCPs, up to 75 mm in diameter. Diameters of 40 mm and 25 mm are more common. The MCPII is designed for high gain or fast gating applications with moderate to high resolution. Planar diode image intensifiers are designed to provide low noise, high resolution, gated images. Image intensifiers used in front of a framing camera require a fast phosphor output screen so that the temporal information in the radiographed scene is not lost due to smearing from long phosphor decay times. Phosphor selection also

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affects system gain due to the spectral matching of the phosphor output to the second photocathode. Photocathode selection can also be impacted by its spectral sensitivity to the radiation-to-light converter emission, which is often blue for fast scintillators. Input and output windows are selected for either fiber optic or lens coupling.

## 2.2 System Performance Parameters

Imaging systems are often calibrated for specific experimental conditions. Typical calibration measurements include limiting resolution, magnification, and a transfer curve. Limiting resolution is defined as the maximum detectable spatial frequency, in line pairs per millimeter (lp/mm), referenced to either the image or object plane. System magnification is the ratio of the CCD pixel size to the corresponding pixel size at the radiographic object. ( $M = \text{image/object}$ ) A transfer curve maps the system signal level versus input energy. The most useful units provide average pixel counts versus input energy density. A transfer curve describes the dynamic range of the system indicating the noise floor, minimum detectable signal, and saturation level and identifies the linear operating region for the system. Detective quantum efficiency (DQE) is a measure of system efficiency and noise characteristics.

Other parameters are used to measure system performance in the frequency domain. Modulation transfer function (MTF), noise power spectra, and DQE are frequency domain parameters<sup>1</sup> used in system modeling. MTF is used to describe system fidelity as a function of input sine wave spatial frequency. Noise power spectrum is used to model the noise contributions over a range of signal levels.

Other useful parameters include signal gain and scene contrast. Signal gain is helpful when comparing the relative signal from one system to another for a constant input. Scene contrast can be a very critical parameter for radiographic imaging systems. For good scene contrast, we look for high resolving power near a bright scene. Scene contrast is degraded when a system has poor low frequency response, indicated by 'tailing' or blurring in a sharp edge response. When edge response not sharp, any scene structure near a bright area may be obscured by roll off in the edge response.

Scene contrast is established by calculating the modulation of a resolution pattern near a bright edge. For camera comparison, a standard measure is needed. We have chosen a relatively coarse resolution pattern (10 lp/mm) for each camera. The optical target used has a clear background with dark bar patterns to allow modulation detail near a bright background to be examined. The square bar pattern modulation is the contrast transfer function (CTF).

Table 1, below, lists some measured values for different types of image tubes. We are interested in generalizing image tube response, by type, in order to help identify typical tube performance. Examples of measurement techniques are discussed later.

	Limiting Resolution (lp/mm)	MTF = 50%, $f_c$ (lp/mm)	Scene Contrast CTF @ 10 lp/mm	DQE @ 430 nm	DQE @ 540 nm
CCD @ -27°C	22	17.8	0.71	0.116	0.306
CCD + Diode	20	8.1	0.57	0.079	0.041
CCD + 40 mm MCP	18	9	0.41	0.053	0.033
CCD + Hi Blue MCP	20	7	0.45	0.114	
Framing Camera	14	4.8	26	.004	

Table 1. A comparison of intensifier performance characteristics

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### 3. MEASUREMENT TECHNIQUES

The measurements discussed in this paper are accomplished using a ring strobe light source in an integrating sphere that illuminates an optical target that is imaged onto the detector system. The target is imaged through a spectral filter to reduce chromatic aberrations for resolution measurements and to perform sensitivity measurements in the spectral region best matching the intended region of radiographic use.

#### 3.1 Resolution Measurements

Limiting resolution is measured by imaging a resolution pattern onto the detector to determine the highest resolvable spatial frequency. For our purposes, we have defined resolvable frequency to be any frequency with better than 5% modulation. From an extracted profile, modulation is defined as:

$$\text{Modulation} = m = (S_{\max} - S_{\min}) / (S_{\max} + S_{\min}),$$

where,  $S_{\max}$  and  $S_{\min}$  are the maximum and minimum signal levels above background, respectively<sup>3</sup>. Sine wave and square wave modulation correspond to MTF and CTF, respectively<sup>2</sup>. The MTF is the output modulation divided by the input modulation as a function of frequency:

$$\text{MTF}(f) = m_{\text{output}}(f) / m_{\text{input}}(f), \quad m_{\text{input}}(f) = 1 \text{ for resolution targets.}$$

Modulation transfer curves are used to view modulation over a spatial frequency range and, in modeling for cascading component MTFs to predict a system response. An MTF curve can be generated by analyzing numerous line pair patterns or by analyzing the system edge response.

We use edge response to calculate MTF curves. A profile is extracted from the image to give the edge-spread function (ESF). The ESF is then differentiated to produce a line-spread function (LSF). The Fourier transform of the LSF gives the MTF curve<sup>1</sup>.

$$\text{MTF} = F(d(\text{ESF})/dx) = F(\text{LSF})$$

Scene contrast CTF is calculated as shown below with values taken from the modulation profile in Figure 1.

$$S_{\min} = 12.75 - 10.94 = 1.81, \quad S_{\max} = 12.75 - 6.06 = 6.69$$

$$\text{CTF} = (S_{\max} - S_{\min}) / (S_{\max} + S_{\min}) = (6.69 - 1.81) / (6.69 + 1.81) = 0.57$$

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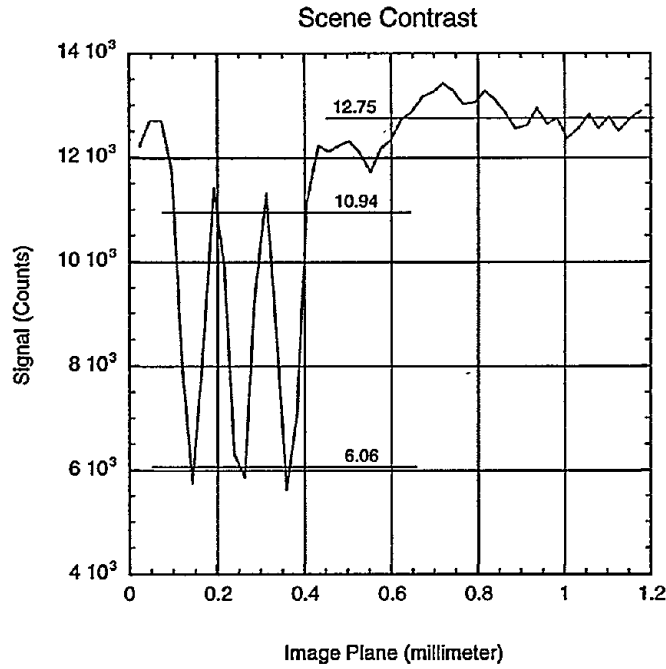


Figure 1. A typical scene contrast plot, a 10 lp/mm bar target is resolved with 57% modulation against a bright background.

### 3.2 Detective Quantum Efficiency

Detective quantum efficiency is used to measure system sensitivity and noise characteristics. DQE is the square of the output signal-to-noise ratio divided by the square of the input signal-to-noise ratio<sup>1</sup>. The ideal detector has a DQE equal to one. We are measuring DQE of the detector over a many pixel area, approximately 10,000 pixels. This technique calculates DQE in a low spatial frequency response range, which facilitates the removal of fixed pattern noise.

$$DQE = (S/N)_{out}^2 / (S/N)_{in}^2.$$

$$(S/N)_{in}^2 = (q/q^{1/2})^2 = q, \text{ quanta input.}$$

The quanta input is measured with an energy meter in joules (J). The input energy is then converted to number of photons per resolution element as follows<sup>4</sup>:

$$q_p = Q_e / [(A_D)(eV)(hc/e)/\lambda],$$

where:  $q_p$  = photons per pixel,  
 $Q_e$  = irradiant energy (Joules)  
 $A_D$  = Area of detector illumination (pixels)  
 $eV = 1.6022 \times 10^{19}$  J (electron energy)  
 $hc/e = 1.23985 \times 10^{-6}$  V m  $\approx$  1240 eV nm (volt-wavelength conversion)  
 $\lambda$  = input wavelength (nm)

$$q_p = Q_e / [(A_D)(1.6022 \times 10^{19})(1240/\lambda)],$$

$$q_{res.el.} = q_p / A_{res.el.} = \text{photons per resolution element.}$$

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$A_{res,el}$  = area of a resolution element in pixels.

The area of a resolution element is determined experimentally using a point source illumination. A single mode fiber, 6-micron core, is used as a point source illumination on the detector. The point source image is background subtracted, then normalized to one. The area of illumination is then integrated to determine the number of total pixels in the spatial impulse response. Ideal resolution element size is one pixel (a lot of spread in the impulse response results in many pixels comprising a resolution element).

Signal-to-noise out is defined as the mean signal divided by the standard deviation in the signal after fixed pattern noise has been removed. Fixed pattern noise can be removed by dividing two flat field images or by averaging multiple flat field images. Using two images is less labor-intensive but loses track the mean signal value.

Two image method:

Signal noise is determined by subtracting two flat field images to remove the fixed pattern noise.

Signal noise = standard deviation (flat1-flat2) /  $2^{1/2}$ .

Ten image method:

Ten flat field images are summed then normalized to one. The corrected flat field is divided into a signal image to remove fixed pattern noise. Signal noise = standard deviation (corrected signal). This technique has the advantage of retaining the mean signal values.

For MCP image intensifiers, DQE measurements are found to vary with MCP gain voltage as shown in Figure 2.

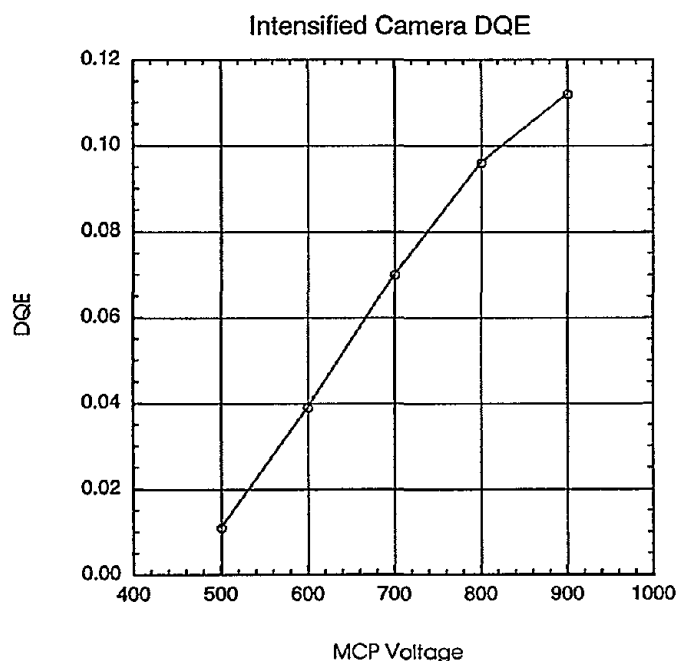


Figure 2. Intensified camera DQE as a function of MCP voltage.

### 3.3 Dynamic Range

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The dynamic range of a system is measured with a transfer curve, which maps the output signal as a function of input energy density. Figure 3 shows a transfer curve of a MCP-II at two different gain settings. Both gain settings allow CCD saturation before MCP saturation is reached. The higher gain setting has both higher sensitivity and higher noise. The dynamic range of the system is the ratio of the saturation threshold input energy to the minimum detectable signal level. The minimum detectable signal is identified as the input energy needed to produce a signal-to-noise ratio of 2 to 1. The minimum detectable signal level is approximately two times the noise equivalent or noise equivalent quanta (NEQ) level. For the transfer curves in Figure 3, the output is linear over the entire dynamic range; therefore, the linearity equals the dynamic range.

For gain 10x, linearity =  $1 \times 10^{-6} / 4.64 \times 10^{-11} = 2.16 \times 10^4$ .

For gain 100x, linearity =  $1 \times 10^{-8} / 3.08 \times 10^{-12} = 3.25 \times 10^3$ .

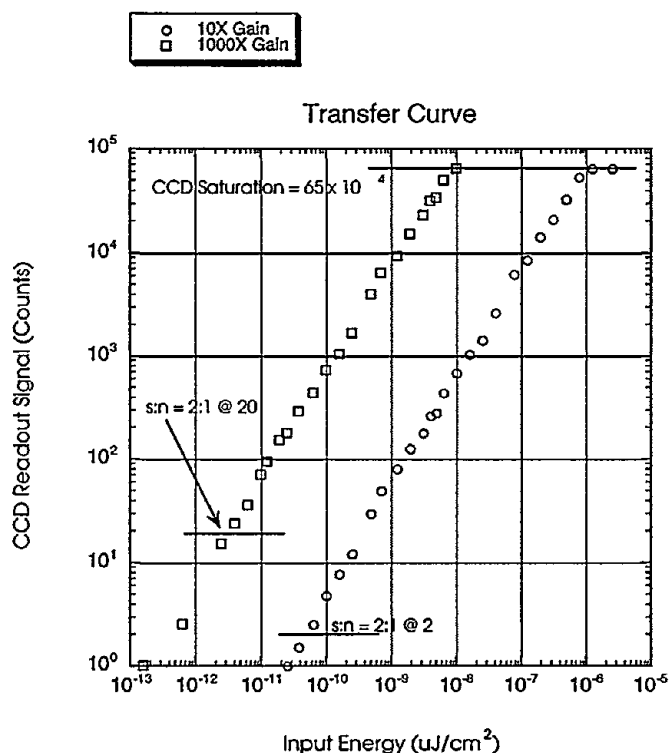





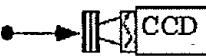
Figure 3. MCP intensified CCD transfer Curve at two different gain settings.

### 3.4 Phosphor Coupling

Image intensifiers are sometimes positioned in front of a second image tube, such as a framing tube, when additional gain or wavelength shifting will improve system response. The phosphors used on intensifiers employed in this fashion must have decay times that are as short, or shorter, than the desired framing time. The gain study below indicates the relative gains of three different systems that incorporate planar diodes with different phosphor screens. Some of these results were presented in *Large Format Radiographic Imaging*<sup>5</sup>, which compared the relative gains of various components viewing a blue light source, and considered spectral shifting issues of the phosphor matching to the second photocathode or CCD sensitivity.

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## Gain Study

	Relative Gain (Counts)	Resolution (lp/mm)	Phosphor Decay <sup>2</sup>
	1	36	
	7.1	20	80 ns
	23	22	1.2 ms
	7.5	16	160 ns







					
P-47 Strobe	P-43 MCP @ 450v	f-o taper	P-47 diode	P-43 diode	P-46 diode

Figure 5. Relative gain of phosphor screens.

## CONCLUSION

This work is part of an ongoing effort to improve image quality in electronic recording of radiographic images. We continue to investigate the potential benefits of various electro-optical devices. Further investigation is needed into tradeoffs between using lenses for magnification and electro-static minifiers, also in phosphor selection in image intensifiers for gain with wavelength shifting, timing, and resolution issues associated with intensifier use in front of framing tubes. We are in the process of developing a standard set of camera system evaluation tests in a software package. This package will enable the user to acquire a complete data set and process the data in a stand-alone package. The package will simplify the processing now associated with generating this type of data. The camera evaluation package will provide a consistent method of obtaining system performance and modeling information.

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