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Streak camera dynamic range optimization*

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ABSTRACT

The LLNL optical streak camera is used by the Laser Fusion Program in a wide range of applications. Many of these applications require a large recorded dynamic range. Recent work has focused on maximizing the dynamic range of the streak camera recording system.

For our streak cameras, image intensifier saturation limits the upper end of the dynamic range. We have developed procedures to set the image intensifier gain such that the system dynamic range is maximized. Specifically, the gain is set such that a single streak tube photoelectron is recorded with an exposure of about five times the recording system noise. This ensures detection of single photoelectrons while not consuming intensifier or recording system dynamic range through excessive intensifier gain. The optimum intensifier gain has been determined for two types of film and for a lens-coupled CCD camera.

We have determined that by recording the streak camera image with a CCD camera, the system is shot-noise limited up to the onset of image intensifier nonlinearity. When recording on film, the film determines the noise at high exposure levels.

There is discussion of the effects of slit width and image intensifier saturation on dynamic range.

1. INTRODUCTION

Streak cameras are being used in an increasing number and variety of applications. There is a continuing effort to improve performance factors such as temporal and spatial resolution and dynamic range. Much of this effort is directed at improving streak tube performance. However, in many applications overall system performance is limited by the image intensifier or the image recording system. Streak camera users seek image recording systems that add negligible degradation to those performance parameters most important to their application. However, other constraints (operational, economic, availability) often result in the use of image recording systems that limit the overall streak camera system performance. This paper presents an approach to the selection and "fine tuning" of a streak camera system with respect to a single performance characteristic, dynamic range.

In the course of this presentation, two image recording systems of interest to the Laser Fusion Program at the Lawrence Livermore National Laboratory (LLNL) are presented. These are:

1) Contact recording onto film.
2) Lens-coupled recording onto a charge-coupled device (CCD).

Although our examples are for a specific streak camera (and CCD camera), there is a large degree of commonality with many other streak cameras and image recording systems. Hopefully these examples are of value to the community at large.

A streak camera system is made up of several discrete components (Fig. 1). At the heart of the system is the streak tube; but other components also contribute to the overall system performance, particularly dynamic range. Let us at this point present a qualitative definition of the process of "optimizing dynamic range."

The dynamic range is optimized by maximizing the useful information about the source within a single resolution element. The size of the resolution element may depend on the recording system, but is assumed to be fixed for any given recording system. In comparing the dynamic range of different recording systems, the relative sizes of the resolution elements must be accounted for. A larger resolution element will result in a larger

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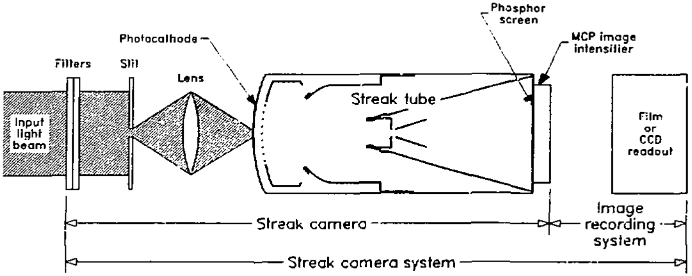

Figure 1. Streak camera recording system. In addition to the streak tube, the system includes input optics, image intensifier, and an image recording system.

dynamic range, but with a concurrent decrease in the number of independent data points in the image.

Frequently when we are called upon to make a measurement the type of streak camera is *predetermined by what is available. In the examples of this paper we are optimizing* the dynamic range of LLNL Laser Fusion Program optical streak cameras.[1,2] The optimization process, however, will work for any streak camera.

2. OPTIMIZATION PROCESS

For a given streak camera system there are a limited number of possible adjustments that control dynamic range. These are:

Input slit width,
Image intensifier tube gain, and
Image recording system selection, e.g., film or CCD and type of coupling technique.

We use the following steps to optimize a streak camera system's dynamic range:

1) Strive for a quantum noise limited (QNL) system at all signal levels.
2) Maximize the number of quanta that can be recorded.
3) If the signal is source limited, increase the detection sensitivity.

Once an image recording system is selected, its noise characteristics can be measured. The gain of the streak camera system (generally including an intensifier stage following the streak tube) can be made high enough that single streak tube photoelectron events are above the noise level of the image sensor. This ensures a QNL system at the lowest detectable signal level. Image sensor characteristics determine if the system is QNL at higher levels. A demonstration of the relationship between system gain and threshold detection S/N is shown in Fig. 2.

The second step is to maximize the number of streak tube photoelectrons that can be recorded. It is important at this point to determine what sets the upper limit of the useful dynamic range. For typical streak camera systems, four possible limits to the signal dynamic range are:

1. Source strength (source limited).
2. Streak tube linearity (streak tube limited).
3. Image intensifier tube linearity.
4. Sensor saturation (sensor limited).

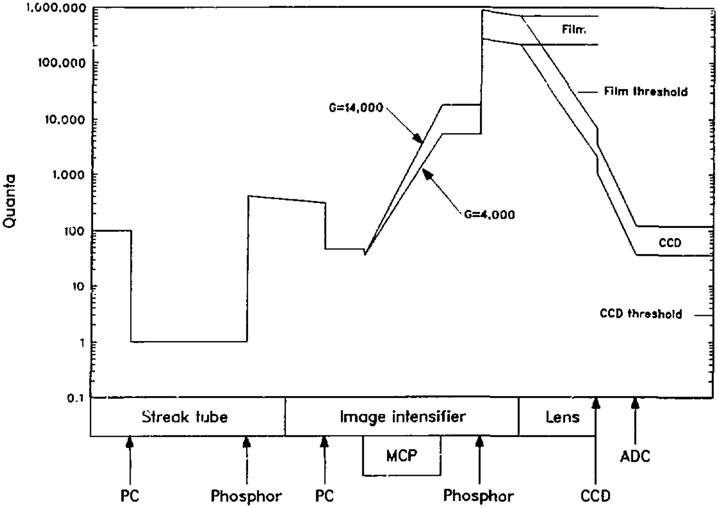

Figure 2. Number of quanta available to communicate the minimum detectable element of information. As information conveying signal intensity passes through a streak camera recording system, it undergoes gains, losses and conversions. The magnitude of the signal at any point in the system can be described as a number of quanta; i.e., electrons or photons. The detection threshold is defined where the number of quanta is a minimum. The minimum detectable element is a single quantum at this point. In a streak camera, this point is generally the photoelectron emitted from the streak tube photocathode. On this graph that level has been set to unity so that the number of quanta at any point represents the minimum meaningful level of information. Curves are for two IIT gains and for two different recording schemes.

Source limited

If the source fluence limits the maximum recordable signal, then the dynamic range will be improved only by increasing the solid angle of the collection optics. In some cases this can be done by increasing the input slit width to the largest opening commensurate with required temporal resolution.[3] For the LLNL streak camera this might be as great as 1 mm.

Streak tube limited

With adequate source fluence, the next limitation may be saturation of the streak tube, generally considered to be space charge effects at the photocathode.[4-6] This is most noticeable for short pulses resulting in large instantaneous photocathode current density. The solution here is similar to that for the source-limited case. By increasing the slit width the current density is reduced (for a given output intensity). Thus, a greater number of photoelectrons can be linearly recorded.

Image intensifier tube linearity

The next element that may saturate is the image intensifier tube (IIT), specifically its microchannel plate (MCP). The MCP behaves much like a segmented parallel plate capacitor with a voltage of about 700 V across it. Because the time it takes to recharge a discharged segment is on the order of milliseconds, only the charge stored in the MCP is available during the much shorter (10's of microseconds) decay time of the streak tube phosphor. Since the output of the IIT is limited, the number of streak tube photoelectrons that may be linearly amplified will be increased by reducing the IIT gain. This may appear to conflict with the initial objective of having a high enough gain that a single photoelectron is detectable by the recording system. In fact, our initial objective is simply modified to set the IIT gain high enough that a single photoelectron is "barely detectable" by the sensor. While "barely detectable" is a qualitative assessment, we use a gain such that a single photoelectron creates a peak signal five times the sensor noise.

Sensor limited

Finally, the sensor itself may saturate. For example, film D-log E curves may flatten out or the full well capacity of a CCD pixel may be exceeded. The solution here is the same as for a saturated IIT; i.e., operating at the smallest acceptable IIT gain.

3. APPLICATIONS/EXAMPLES

We present two examples of dynamic range optimization that have been used in LLNL's Laser Fusion Program on the Nova laser system. The first is the selection and optimization of a contact film image recording system. The second is a lens-coupled CCD imaging system.

Contact recording onto film

In this classical recording technique, the emulsion of a photographic film is placed in contact with the fiber-optic faceplate on the streak camera IIT output. We first select the best film available and then adjust the IIT gain for maximum dynamic range.

Film selection. For many years Kodak Royal-X Pan film was used for streak camera recording. It was chosen because of its high speed and our experience in using it for oscilloscope recording. We investigated two other films and ultimately selected Kodak Tri-X for subsequent recording of streak camera images. This selection was based on the data shown in Fig. 3. Here a signal-to-noise (S/N) ratio is presented for a wide range of exposures. Figure 3 shows that Tri-X and Royal-X Pan have similar threshold sensitivities. At higher exposure levels, however, Tri-X has superior S/N because its D-log E curve has less flattening than Royal-X Pan's. Kodak Technical Pan film has a very high peak S/N, but has poor sensitivity and a relatively small dynamic range.

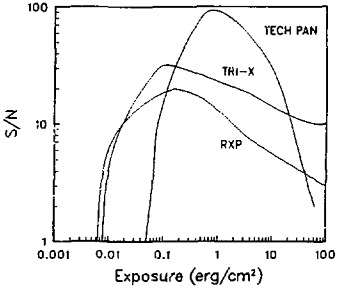

Figure 3. Signal-to-noise characteristicss of three types of film. The S/N of film is dependent on film type and on exposure level. (Pixel area is 4000 μm^2.)

IIT gain adjustment. The measurements of Fig. 3 were repeated with the film exposed through a streak camera system. Figure 4 shows the results using Tri-X film at two IIT gains, 5000 and 14000 (luminous). In this case the S/N is degraded due to the addition of quantum photoelectron noise. The S/N is better at the lower IIT gain because more photoelectrons are required to attain a given exposure. In order to obtain a uniform image, these measurements were made by operating the streak tube as an image converter; i.e., the extraction grid is 180 V relative to the cathode rather than the 2200 V when used in the streak mode. This does not affect the photoelectron energy at the streak tube phosphor screen. (Note: The absolute value of the gain, and even how the gain is defined, are not important. The selection of the optimum gain setting is only dependent on the S/N of the sensor at the exposure due to a single photoelectron event.)

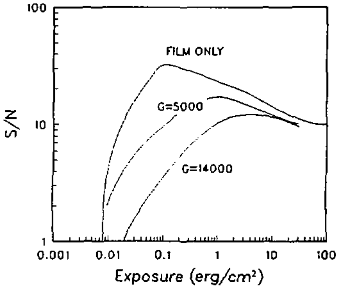

Figure 4. Signal-to-noise characteristics of a streak camera image recorded on film. The top curve is the Tri-X curve from Fig. 3. The other two curves include the noise contributed by the streak camera IIT at luminous gains of 5000 and 14000.

At a gain of 5000 the image is QNL from threshold to about 0.2 erg/cm^2. At higher exposures, the film limits the S/N, totally dominating at exposures above 2 erg/cm^2. Thus, we see that even though Tri-X film is an improvement over Royal-X Pan, the film remains the limiting factor over a large part of the operating range.

As a result of these measurements, we determined that at an IIT gain of ∿4000 (luminous), a single photoelectron generates an intensity that is ∿5 times Tri-X film noise.

Lens-coupled CCD recording

We are now using a lens-coupled CCD camera in several applications to record streak camera images. This camera[7] uses a thermoelectrically cooled CCD and a 14-bit A/D converter. It is coupled to the IIT by an f/1.4 lens operating at a 2.5 to 3:1 image reduction.

This camera was characterized in much the same manner as film, described in the previous section. The results are shown in Fig. 5. There are two CCD curves shown, along with that for Tri-X film for comparison. The lower CCD curve represents an image that is not corrected for variations in sensitivity among pixels. This curve flattens out to a maximum S/N of ∿125 at high exposures due to fixed pattern noise. The upper CCD curve has been corrected by flat-field correction to remove fixed pattern noise in the CCD.[6] It is worth noting that this correction is not possible with film.

The CCD noise (excluding fixed pattern noise) is largely determined by the number of electrons in the CCD pixel. A straight line showing theoretical quantum limited noise of a single image is also shown on Fig. 5. At low exposures the S/N of the corrected image is poorer than that for the uncorrected image. This is because the corrected image includes the random noise due to two images, the signal and flat-field images. At high exposures the corrected image shows dramatic improvement because the fixed pattern noise has been removed.

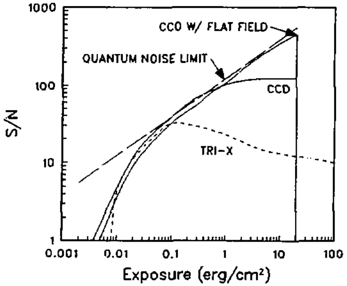

Figure 5. Signal-to-noise characteristics of the LLNL CCD camera. The two CCD curves represent performance with (upper) and without (lower) flat-field correction. With correction, the CCD noise is essentially defined by the number of electrons in a pixel. Without correction, fixed pattern noise dominates at high exposures. Tri-X film performance is shown for comparison. (Pixel area is ~4000 μm^2 at the IIT.) Vertical line shows CCD full well capacity corresponding to 20 erg/cm^2.

In contrast to film, the CCD has a hard upper limit to its operating range. This is due to the CCD full well capacity, the maximum number of electrons a CCD pixel can hold.

IIT gain adjustment. The S/N characteristics of the streak camera system were measured using the same process as for film. For these tests, the fixed pattern noise was not removed. Figure 6 shows the results for two IIT gains, along with the uncorrected CCD response. As with film, the S/N is better at the lower IIT gain. There is, however, a significant improvement in overall performance as compared to film as shown in Fig. 6.

We found that an IIT gain of ~4000 is optimum (Fig. 7). (Coincidentally this is the same value as when contact recording onto Tri-X film.) At this gain a single photoelectron generates a signal about 5 times the CCD camera noise. The slightly poorer resolution of the CCD camera as compared to film makes this a conservative choice. Nonetheless, the recording system is QNL for about three decades--a dynamic range of 1000:1.

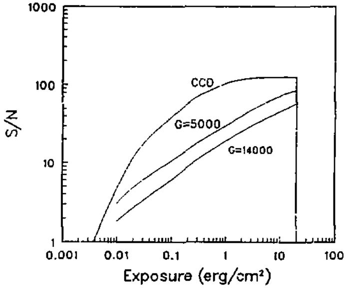

Figure 6. Signal-to-noise characteristics of a streak camera image recorded by a CCD camera. The top curve is the uncorrected CCD curve from Fig. 5. The other two curves include the noise contributed by the streak camera at IIT luminous gains of 5000 and 14000.

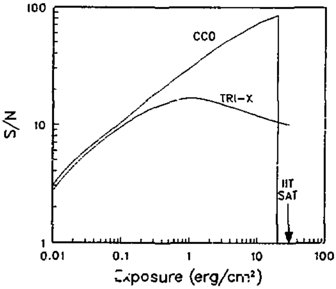

Figure 7. Comparison of streak camera performance using Tri-X film and the CCD camera. In each case the IIT gain was set to generate a peak single event signal intensity which produces a S/N of 5.

4. IMAGE INTENSIFIER TUBE SATURATION

As part of our dynamic range work, we studied the saturation characteristics of Generation II image intensifier tubes. These tubes are frequently used to amplify a streak tube image. As described earlier, the maximum output of a pulsed IIT is limited to the charge stored in its MCP. This charge is typically 4×10^{-9} coul/cm^2. When fully discharged into the phosphor screen, this results in about 30 erg/cm^2 of green (P-20 phosphor) light at the output of the intensifier.

We found that the intensifier has a gradual saturation curve (Fig. 8). Significant nonlinearity can be a factor at output intensities as low as 30 percent of hard saturation.

5. PHOTOCATHODE SATURATION/SLIT WIDTH

There are streak camera applications where the current density at the streak tube photocathode limits the upper end of the dynamic range. Saturation is manifested as an apparent temporal pulse broadening of the output image. The effect is most noticeable for very short pulsed illumination. By widening the input slit, the current density is proportionately reduced for a given output intensity. The effects of slit width are demonstrated in Fig. 9. These data were taken in the "static" mode of streak camera operation, with 50-ps laser pulse illumination. There is a pulse broadening due to the IIT saturation at a CCD amplitude of ~8000 counts, but additional broadening occurs if the streak tube current density is excessive. In this case, slit widths smaller than 400 μm show some premature pulse broadening.

It should be noted that the static mode is most sensitive to this saturation. In the swept mode the broadening will add in quadrature with the properly recorded image width. Thus, Fig. 9 presents the most pessimistic characterization of pulse broadening for this pulse width. Shorter pulse widths, however, will result in image broadening at lower intensities than shown here.

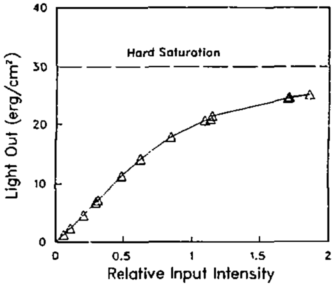

Figure 8. Generation II image intensifier tube saturation characteristics. These data were taken on an IT&T F4126 single-stage MCP photomultiplier tube. It is physically similar to the F4113 image intensifier tube, except an anode replaces the phosphor screen. There is some nonlinearity even at relatively low input levels.

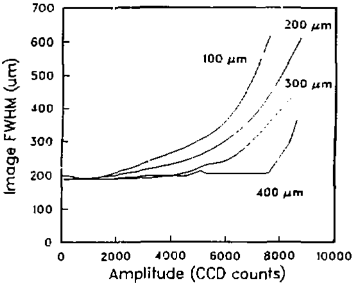

Figure 9. Static determination of the onset of signal saturation for various input slit widths. Pulse broadening due to IIT saturation begins at CCD exposure corresponding to about 8000 A/D counts; small slit widths may cause premature broadening in the streak tube because of high current densities at the photocathode. These data were taken with 50-ps, 532-nm light pulses.

6. FURTHER IMPROVEMENTS IN STREAK CAMERA MEASUREMENTS

After a streak camera system is adjusted for maximum dynamic range, there are still limitations to the accuracy of the measurements. A very important limitation is due to spatial gain variations across the image. Once the swept image has been transformed from the time domain to space domain at the streak tube screen, each image pixel is independently amplified and recorded. Due to manufacturing limitations, the range of amplification across the tube may be great; 2:1 is not unusual for an IIT. Fortunately, the spatial variations in gain are primarily time invariant. Accurate characterization of the streak camera system allow for correction for gain variations. This process is described in a related paper[8] in these proceedings.

7. ACKNOWLEDGMENTS

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