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Flat-field response and geometric distortion measurements of optical streak cameras*

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ABSTRACT

To accurately measure pulse amplitude, shape, and relative time histories of optical signals with an optical streak camera, it is necessary to correct each recorded image for spatially-dependent gain nonuniformity and geometric distortion. Gain nonuniformities arise from sensitivity variations in the streak-tube photocathode, phosphor screen, image-intensifier tube, and image recording system. These nonuniformities may be severe, and have been observed to be on the order of 100% for some LLNL optical streak cameras. Geometric distortion due to optical couplings, electron-optics, and sweep nonlinearity not only affects pulse position and timing measurements, but affects pulse amplitude and shape measurements as well.

By using a 1.053-μm, long-pulse, high-power laser to generate a spatially and temporally uniform source as input to the streak camera, the combined effects of flat-field response and geometric distortion can be measured under the normal dynamic operation of cameras with S-1 photocathodes. Additionally, by using the same laser system to generate a train of short pulses that can be spatially modulated at the input of the streak camera, we can effectively create a two-dimensional grid of equally-spaced pulses. This allows a dynamic measurement of the geometric distortion of the streak camera.

We will discuss the techniques involved in performing these calibrations, will present some of the measured results for LLNL optical streak cameras, and will discuss software methods to correct for these effects.

1. INTRODUCTION

The Nova laser facility at the Lawrence Livermore National Laboratory (LLNL)[1] is able to perform complex temporal shaping of the laser pulse used to irradiate targets for inertial confinement fusion experiments. LLNL designed streak cameras[2,3] are routinely used to obtain time resolved measurements of the laser power and various target emissions for each experiment. For certain experiments, and particularly for pulse-shaped implosions, it is necessary to know the laser power and target emissions accurately (<10% error) in order to understand and control the complex physics involved. Effects such as image gain nonuniformities and geometric distortion can introduce significant (>50%) errors in both spatial and temporal measurements. The primary concern of the work presented in this paper has been to characterize these effects in the optical streak cameras used for laser power measurements and to apply a correction to the measured data.

1.1 Errors in streak camera measurements

There are several sources of error in making quantitative measurements with a streak camera system. The largest contributors are:

1) Image gain nonuniformities
2) Geometric distortion (including sweep nonlinearity)
3) Nonuniform background (dark current)
4) Spatial and temporal resolution limits
5) Random noise
6) Dynamic range limits

This paper deals mostly with the effects of image gain nonuniformities and geometric distortion. Nonuniform background, although usually a small effect, is accounted for in this presentation but will not be discussed at length. The last three sources of error, resolution limitations, random noise, and dynamic range limitations, are discussed at length in other papers in these proceedings[4,5] and have been optimized for this work.

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1.2 Effects of gain nonuniformities and geometric distortion

Nonuniformities in the image gain are attributed to sensitivity variations in the streak-tube photocathode, phosphor screen, image-intensifier tube, image recording system, and to transmission variations in the input and output optics. Geometric distortion due to the streak camera optics, electron-optics, and sweep-rate nonlinearity not only affects signal position and timing measurements, but affects signal amplitude and shape measurements as well.

To characterize the effects of gain nonuniformities and geometric distortion in an imaging system, the response to a uniform or known input signal is measured. For a streak camera system a spatially and temporally uniform input signal is used to generate an output signal, called the flat-field response. Since the input signal is flat in amplitude, the flat-field response gives the point-for-point amplitude response due to the effects of system gain nonuniformities and geometric distortion. Nonuniformity in the flat-field response can be used to correct arbitrary input signals for their distortions, and therefore improve the accuracy of the measurement. The transformation between input signal and output signal is given by the equation

$$I_i(x,t) = I_0(x',y') \; [G(x',y') \; J(x',y')] \tag{1}$$

$$J(x',y') = \frac{dx' \; dy'}{dx \; dt} \tag{2}$$

where (x,t) are the input coordinates, (x',y') are the output coordinates, I_i is the input signal, I_0 is the output signal, G is the gain function, and J is the Jacobian transformation from (x,t) to (x',y'). If the input signal is flat, i.e. $I_i(x,t)$ is constant, then the output measured signal, $I_0(x',y')$, is basically the reciprocal of the flat-field response (the product of G and J). To use this characterization to correct input signals, simply multiply the measured output image by the normalized flat-field response image. This task is easily performed with a mini-computer, taking only a few seconds of CPU time for two 0.5 Mbyte images.

To characterize the geometric distortion produced by the streak camera, a spatial and temporal "grid" of equally spaced pulses is generated as the input signal and the distorted image produced by the streak camera is recorded. Since the grid at the input has a constant spacing in both the spatial and temporal directions, the nonlinear spacing in the output image may be measured, and the Jacobian transformation from input to output may be calculated from Eq. 2.

2. MEASUREMENT TECHNIQUES

2.1 Generation of a uniform amplitude source

The streak cameras that were characterized for this work were to be used in a discrete channel application with multiple fiber optic inputs. This meant that while the temporal flatness of the input signal was vital, small spatial nonuniformities in the input signal could be tolerated. To produce a temporally flat light pulse, planar triode amplifiers were tuned to generate a 15-ns, square, high-voltage pulse that drove two Pockels cells. The Pockels cells were timed to slice out a square pulse from the center of a 300-ns Gaussian pulse produced by a 1.053 μm, YLF, single-mode, laser oscillator[6]. Using this scheme, the flatness of the pulse is a few percent.

2.2 Measurement of flat-field response

The flat pulse was used to illuminate the entrance slit of the streak-tube photocathode and the electrons emitted were deflected across the streak-tube phosphor screen at rates between 100-300 ps/mm. The resulting output images were recorded on a CCD camera system. The recorded image is the response through the entire streak camera system, and the nonuniform effects contributed by individual components of the system are not determined by this technique. As an example, Fig. 1 shows an averaged scan (lineout) taken in the time direction of a typical flat-field response image. Nonuniformities in excess of 100% can be seen in this data.

2.3 Verification of flat-field response

Two experiments were performed to verify that modulations seen in the output image of the streak camera were caused by the flat-field response and not by input signal modulations. The first was simply to change the timing of the camera trigger with respect to the input pulse. With this type of experiment, shifting modulations in the output image

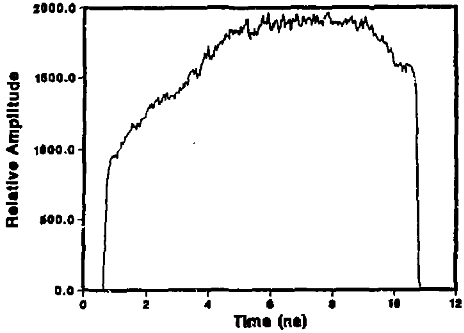

Figure 1. Streak camera temporal response to a flat pulse input. This measurement is called the flat-field response of the camera.

are caused by the input signal; those that do not shift are due to the flat-field response. Lineouts taken in the time direction of two flat-field response images for the same camera are shown in Fig. 2. The trigger time has been shifted 2-ns for one of the images. The two profiles show the same trend and differ mostly in the higher frequency noise. This indicates that the modulation seen in the output image is the result of the flat-field response rather than modulations of the input.

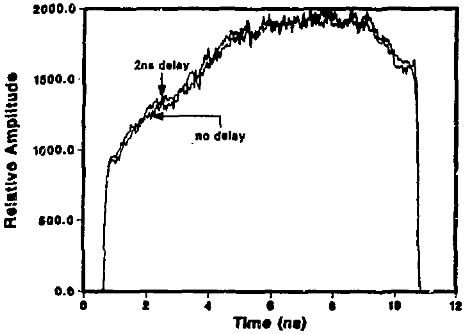

Figure 2. Verification of flat-field response by shifting the camera trigger timing. The trigger time has been delayed 2-ns for one of the images.

Alternatively, we used short pulses of equal intensity to verify the flat-field response. By varying the trigger timing, the pulses can be displayed on different areas of the output image. The output intensity varies as the flat-field response of the camera. This verifies the previously determined response function at discrete points. Figure 3 shows an example of this experiment performed on a camera with severe gain nonuniformity in the temporal direction.

2.4 Linearity of flat-field response

The flat-field response of a particular streak camera may not be constant with different input intensities due to effects such as saturation of the image-intensifier tube or image recording system. However, we can expect that it would be constant up to

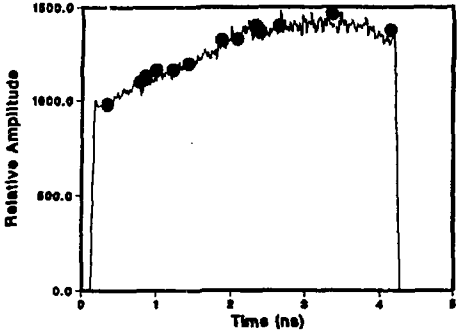

Figure 3. Verification of flat-field response by using short pulses of equal intensity. The solid curve is the measured flat-field response and the individual points are the measured signals from equal intensity short pulses.

some given maximum intensity. By adjusting the amount of neutral density filters at the input to the camera, the flat-field response was measured to be constant over a factor of at least 15:1 in input intensity. Lineouts of two flat-field response images are shown in Fig. 4 where the input intensity was 15 times greater for one image. As can been seen in the data, the two response measurements agree to within the noise of the measurement.

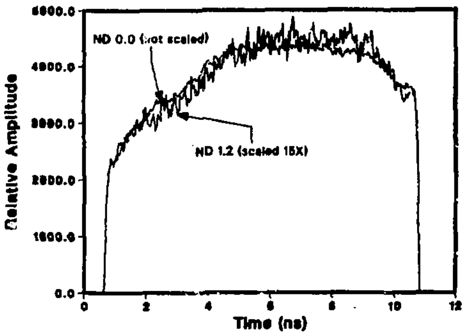

Figure 4. Flat-field response is unchanged over a range of at least 15:1 in input intensity.

2.5 Measurement of geometric distortion

We measure the geometric distortion by creating a streak camera image from a two-dimensional array of pulses. The pulses are equally spaced in time and across the input slit. The temporal spacing is obtained by causing the long-pulse laser oscillator to go unstable, resulting in two axial modes in the cavity. The two modes beat, producing a pulse train with a 250-ps period. This pulse train illuminates a grid pattern at the slit of the streak camera. An example image is shown in Fig. 5. The image is oriented with the time direction being vertical.

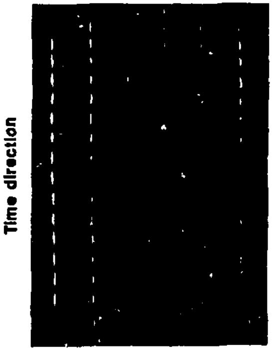

Figure 5. Geometric distortion of a streak camera. Grid illumination by periodic light pulses creates a two-dimensional array of points in the streak camera output image. This image can be used to measure and correct geometric distortions in the streak camera image.

2.6 Calculation of geometric distortion effects

Using the geometric distortion image, the Jacobian transformation may be computed as described earlier. The gain function G(x',y'), from Eq. 1, is independent of geometric distortion and should be the same at different sweep rates because the nonuniformities attributed to it are spatially dependent only. Geometric distortion images were taken for sweep durations of 3.5-ns and 10-ns, and the flat-field response was measured for each. Each image was computer corrected for its corresponding geometric distortion, and lineouts were compared for each. Figure 6 shows an example of lineouts taken in the time direction of two corrected flat-field response images. The two profiles are in good agreement, differing mostly in the higher frequency noise. This result indicates that the flat-field response needs only to be measured at one sweep rate, along with the corresponding geometric distortion image. Then it is necessary only to obtain the geometric distortion image at other sweep rates and compute the flat-field response for each based on the transformation corrections.

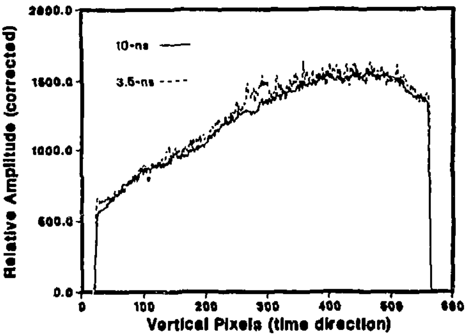

Figure 6. Flat-field response measurement can be corrected for geometric distortion effects. The lineouts show the corrected flat-field response for the same camera operated at two significantly different sweep rates.

3. SUMMARY

We have successfully demonstrated a technique for measuring the flat-field response in the temporal direction. For some LLNL optical streak cameras, the response has been observed to have significant nonuniformities for which the data must be corrected to obtain highly accurate measurements. Future efforts will focus on making the characterization process simpler, routine, and on making the input source spatially uniform.

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