INTERNAL REPORT SDL-86-02

TIME-RESOLVED RECORDING OF LOW INTENSITY OPTICAL SPECTRA IN DYNAMIC EXPERIMENTS

PAUL D. HORN

July 1986

Shock Dynamics Laboratory

Department of Physics

Washington State University

Pullman, WA 99164

Time-Resolved Recording of Low Intensity Optical Spectra in Dynamic Experiments*

P. Horn
Shock Dynamics Laboratory
Physics Department
Washington State University
Pullman, WA 99163

The method described here was developed to record the ruby luminescence R-line spectrum in shock wave experiments; however, it could be applied more generally to experiments in which time-resolved spectra must be recorded in a single-shot mode. The recording system consists of an image converter streak camera, a microchannel plate image intensifier, and an optical multichannel analyzer (OMA). The techniques for achieving good throughput are described, and the role of the OMA scanning parameters in determining the quality of the recorded image is discussed. Observations concerning the signal-to-noise ratio are discussed in the context of signal levels at the image intensifier.

Introduction

The technique presented was developed to observe changes in the ruby luminescence R-line spectrum in shock wave experiments [1]. In these experiments, a ruby sample is subjected to large uniaxial compression (up to a few percent change in density) on a nanosecond timescale. The sample is destroyed in each experiment, so that the spectrum must be recorded over the approximately 1.5 μs time of interest in a single-shot mode. I will first describe the recording apparatus and the techniques for obtaining efficient optical coupling of the components. Next, the scanning parameters of the optical multichannel analyzer will be discussed, and samples of the spectra obtained with this

* The method described here was developed during the course of a research project funded by the Defense Nuclear Agency under contract 001-85-C-0154.

system will be presented. Finally, the observed signal-to-noise level will be examined in connection with the signal intensity at the image intensifier.

Apparatus

The apparatus for generation, collection, and spectral dispersion of the ruby spectrum has been previously discussed [1,2]. For the purpose of describing the recording system, I will simply state that the output of the spectrograph is approximately 7 μW of luminescence, divided between the two ruby R-lines (694.3 nm and 692.9 nm). The recording apparatus is presented in Figure 1. The spectral lines are focused onto the photocathode (point A) of an image converter streak camera (Cordin model 160), generating a corresponding photoelectron image of the spectrum. This photoelectron image is swept at a constant rate across the phosphor (point B) in the direction perpendicular to the spectral axis, producing a record of light intensity as a function of wavelength and time. The streak image is lens coupled onto a microchannel plate image intensifier (ITT F4113, P-11 phosphor) to provide sufficient signal for the detector (EG&G OMA III with model 1254 intensified Vidicon detector). A significantly higher throughput could be achieved if the streak camera output were coupled fiberoptically, but this was not possible with the available camera. The length of the streak is 50 mm (time direction), and the width of the spectral axis is 19 mm. The useful area of the Vidicon detector is a 12.5 mm square, so that reduction of the streak image is necessary. Since the output of the image intensifier (point D) and the input of the Vidicon detector (point E) are both fiberoptically coupled, the image is reduced by a factor of three using a tapered fiberoptic bundle (Galileo Electro-Optics), and high throughput is maintained.

The image transmitted by a fiberoptic bundle is only "in focus" immediately at the surface of the bundle, and defocusing occurs rapidly with distance. It is therefore critical that fiberoptic couplings be made with very little gap or tilt between components to avoid loss of resolution. In this system, difficulty occurred because the Vidicon detector face

was not sufficiently perpendicular to the axis of the detector housing, with the tilt amounting to about 7 milliradians. This problem was solved by adjusting the mount holding the tapered fiber bundle to correct for the tilt. The mount was first attached to the Vidicon housing with a locating pin added to prevent rotation about the housing axis. The Vidicon was then held vertically, and the fiberoptic bundle was placed in contact with the detector face and adjusted until good coupling was achieved, as verified by the observing the interference pattern at the bundle/detector interface. The fiberoptic bundle was then potted into the mount with RTV compound. The opposite end of the mount was then machined until good coupling was similarly observed at the image intensifier. Finally, this assembly was lens coupled to the streak camera.

Recording the Streak Image

The Vidicon detector in this OMA system is treated as a 500x500 array of picture elements (pixels). Each pixel stores an amount of charge proportional to the light exposure it receives. The manner in which these pixels are read and processed significantly effects the quality of the digitally recorded image. The layout of the Vidicon screen is shown in Figure 2. The major parameters chosen by the experimenter are the number of pixels to be added into an individual data point or channel, the number of channels to be read and their grouping into tracks, and the length of time taken to collect signal from each channel. This OMA system is configured such that a channel is one pixel wide and a user specified number of pixels tall (channel height). In the ruby experiments, the detector was oriented with the channel height parallel to the time axis of the streak record. At the higher scan speeds (short time per channel), only a portion of the charge image can be collected, decreasing the signal level. In addition to this, a single read event collects only 50-55% of the available signal even at slow speeds [3], making multiple scans of the screen desirable when possible. Since leakage of charge between adjacent channels degrades the image over time, a balance must be found between scan time per channel and the time required to

read the entire screen. In these experiments, the screen layout consisted of 50 tracks (spectra) at 500 channels (wavelength) per track, i.e. the channel height was 10 pixels, for a total of 25,000 data points per record. A scan time of 40 μs/channel and a single scan of the screen (screen time of 1 second) proved to be a reasonable compromise in terms of peak signal level, signal-to-noise ratio, and image quality.

With these scan parameters, the background signal was approximately 200 counts/channel with a random noise of about 10-20 counts per channel (with no light input). The peak signal (plus background) was on the order of 700 counts/channel, as seen in the sample spectrum shown in Figure 3. The time window in these experiments was 1.5 μs, so that each spectrum was integrated over 30 ns. Figure 4 is a 3-D perspective plot of the entire sample streak record, with wavelength increasing from right to left (to make the short wavelength spectral line more apparent), intensity increasing from bottom to top, and time increasing into the page. The signal level at the peak was found to fluctuate randomly by about 100 counts/channel (5-10 time the dark noise), i.e. by 20% of the peak signal (minus background). This can be understood by calculating the corresponding light intensity at the image intensifier.

The sensitivity of the 1254 Vidicon detector is approximately 0.05 counts/photon [2] for light with the P-11 spectral distribution (peaked at 460 nm). Since the screen was only scanned once, about 50% of the available signal was not collected, so that the effective sensitivity was approximately 0.025 counts/photon. The exposure of the detector was thus on the order of 2×10^4 photons/channel (500 counts/channel above background). The transmission of the tapered fiberoptic bundle is about 50% for a Lambertian source, and the photon gain of the intensifier was 690 [4]. Estimating the coupling of the fiberoptic bundle to the detector and intensifier to be 70% efficient, the exposure of the intensifier photocathode (per area corresponding to 1 detector channel) would be

$$E_I = (2 \times 10^4/(0.5)(0.7)(690)) = 83 \text{ photons/channel-equivalent-area} .$$

The S-20 photocathode has a quantum efficiency of about 10% for P-11 light [5], thus, with a probability of 10% that each photon would generate a photoelectron, there were approximately 8 photoelectrons/channel-equivalent-area. The random fluctuations of this number can be estimated according to the Poisson distribution as shown in Figure 5. The width of this distribution is much larger than the observed signal fluctuation, and additional variations are expected at the intensifier output due to the statistics of electron multiplication in the microchannel plate. This probably indicates that the throughput of the system has been underestimated or the effective sensitivity of the detector overestimated; however, the calculation illustrates that while it is possible to record very faint images using an intensifier, the signal-to-noise ratio is decreased due to the statistical behavior of the intensifier.

Conclusion

It has been demonstrated that low intensity optical spectra can be recorded in a single-shot mode using a streak camera, image intensifier, and optical multichannel analyzer. Direct fiberoptic coupling is preferred over lens coupling where possible, but care must be taken in alignment of the fiberoptic faces to maintain good resolution. For very low intensities, the signal-to-noise ratio may be determined not by the detector dark noise, but by statistical fluctuations at the image intensifier (where the intensity is lowest).

References

1. P. D. Horn and Y. M. Gupta, "Wavelength shift of the ruby luminescence R lines under shock compression", Appl. Phys. Lett. 49, 856 (1986).

2. P. D. Horn and Y. M. Gupta, "Ruby fluorescence measurements in shock wave experiments", Proceedings of O-E Lase '86 Conference (SPIE).

3. Doug Malchow, EG&G Princeton Applied Research (private communication).

4. The image intensifier photon gain of 690 was calculated assuming a microchannel plate gain of 66, photocathode quantum efficiency of 10%, accelerating potential of 5000V, phosphor output of 0.086 photons/eV, and fiberoptic faceplate transmission of 50% (each faceplate).

5. Specification for ITT F4113 P-11 microchannel image intensifier.

Figure Captions

Figure 1. Recording Apparatus. The spectrum is focused onto the photocathode of the streak camera (A). The streaked spectrum (B) is then imaged onto the microchannel plate image intensifier (MCP, point C). The intensifier output (D) and Vidicon detector input (E) are directly coupled to a tapered fiberoptic bundle (TFB), providing a 3X reduction in image size.

Figure 2. Layout of Vidicon detector screen. The screen is treated as a 500x500 array of pixels. These are first grouped into channels (one pixel wide and a specified number of pixels tall). The channels are then grouped into tracks (in this case 500 channels per track and 50 tracks per screen).

Figure 3. Ruby luminescence spectrum from a sample streak record (1 track of 50 recorded). Wavelength increases from left to right.

Figure 4. 3-D plot of a ruby luminescence streak record. The spectrum was recorded 50 times over a 1.5 μs period, with each track integrated over 30 ns. Wavelength increases from left to right to allow viewing of the short wavelength spectral line, and time increases into the page.

Figure 5. Poisson distribution for a probability of 10% and a mean value of 8.3 photoelectrons/channel-equivalent-area. For low intensity spectra, statistical fluctuations in the image intensifier can dominate the signal-to-noise ratio.

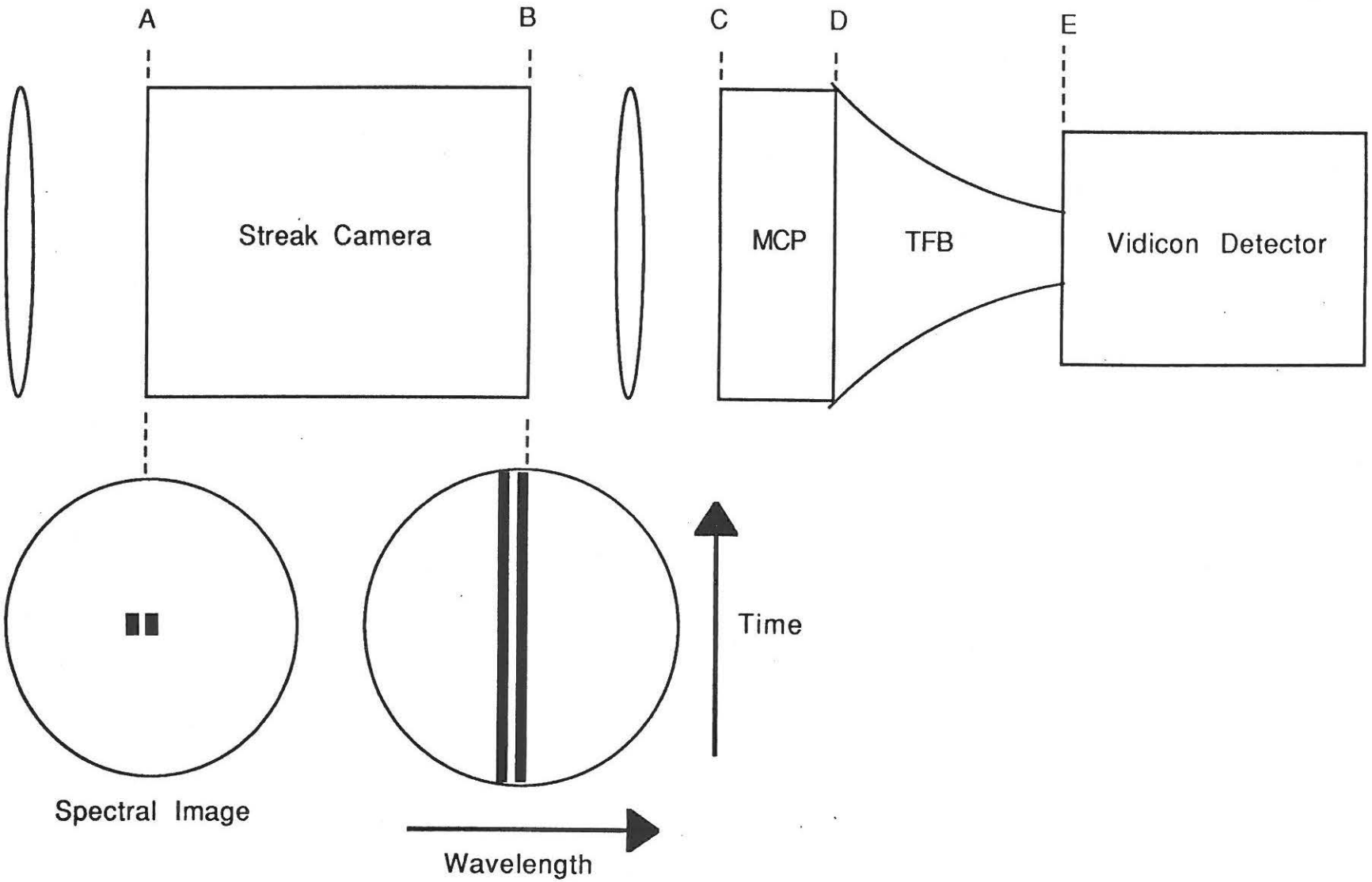

A
B
C
D
E
Streak Camera
MCP
TFB
Vidicon Detector
Time
Spectral Image
Wavelength

Fig. 1

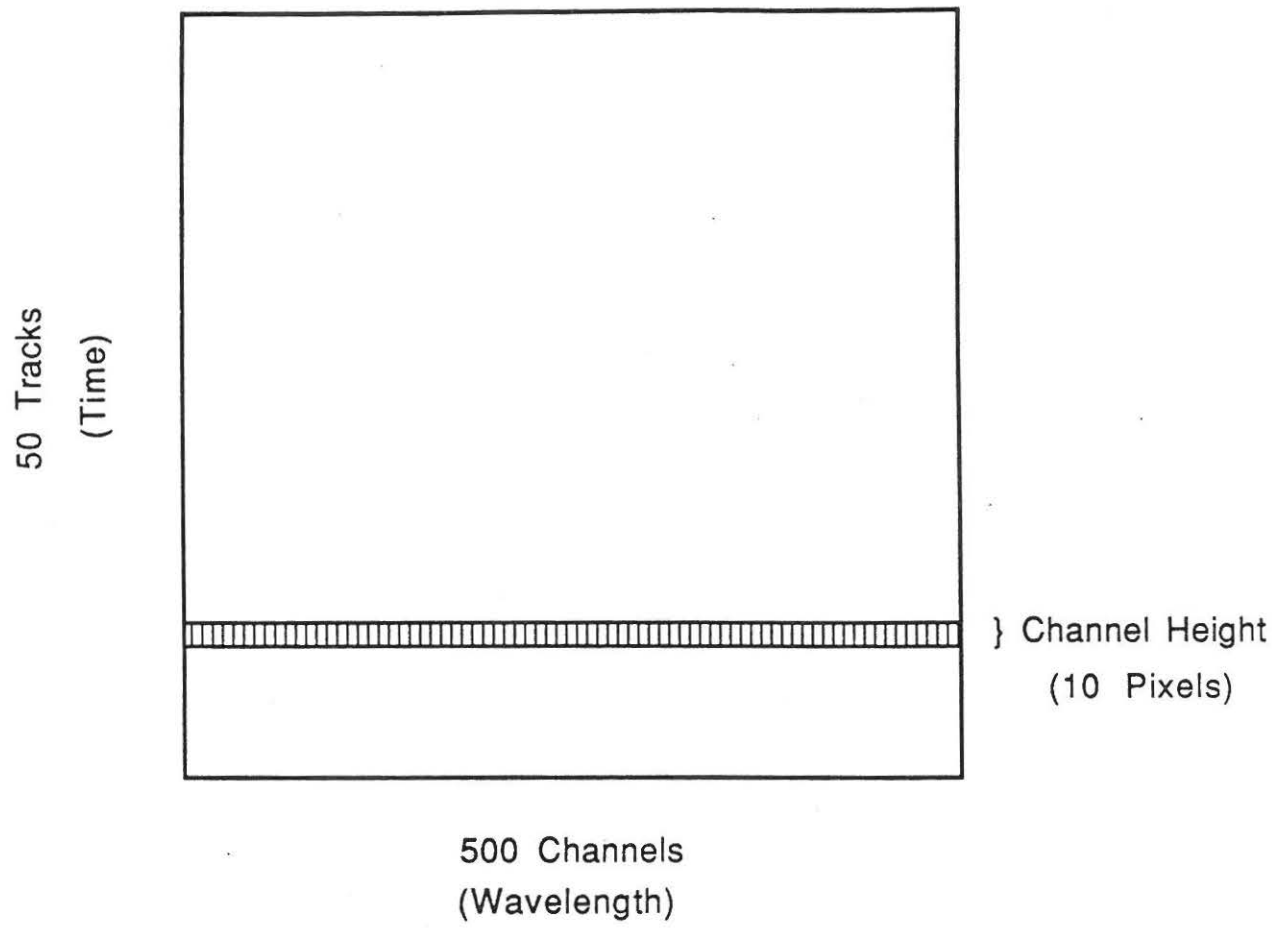
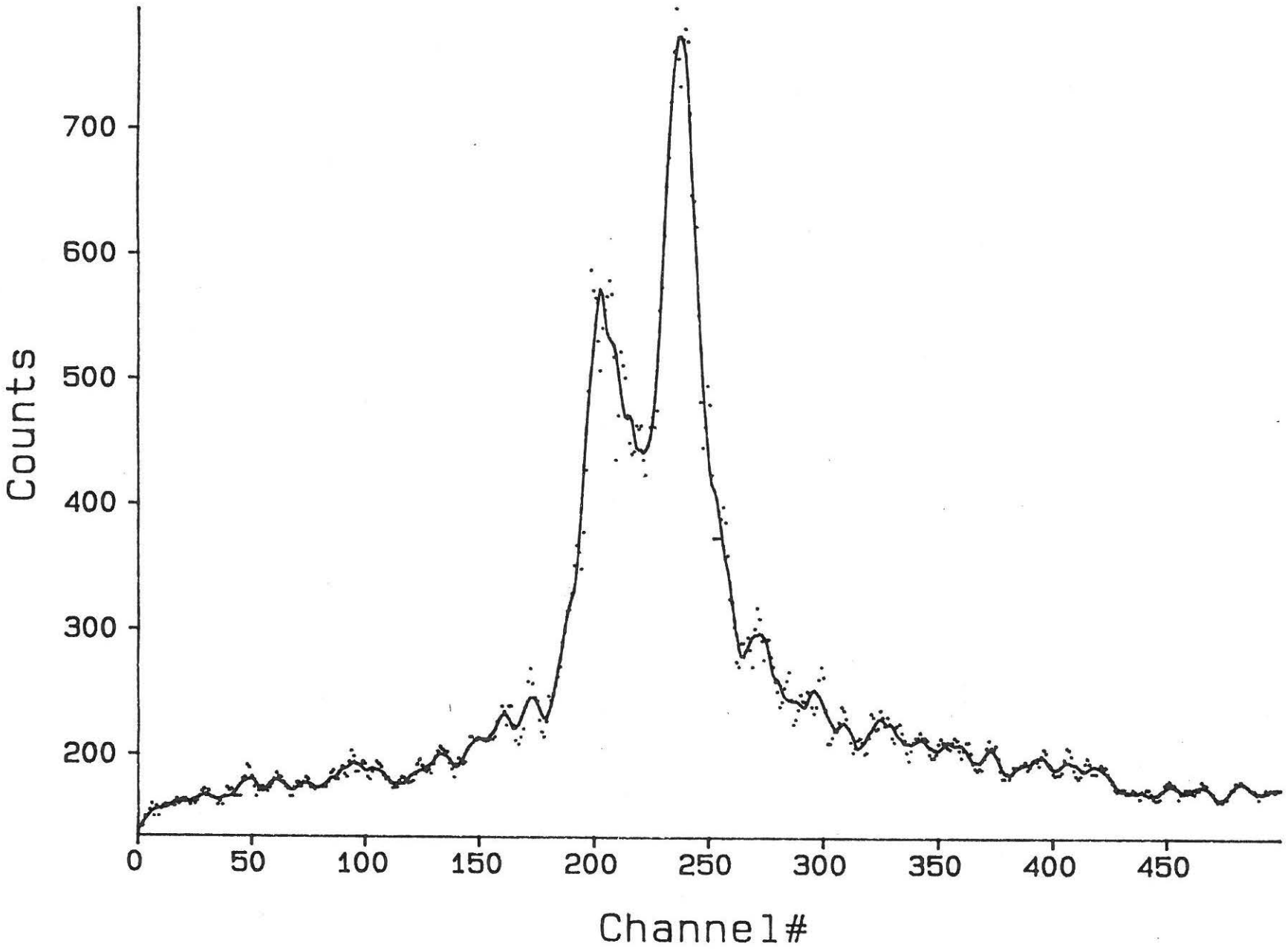

50 Tracks
(Time)
} Channel Height
(10 Pixels)
500 Channels
(Wavelength)

Fig. 2


Counts
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600
500
400
300
200
0
50
100
150
200
250
300
350
400
450
Channel#

Fig 3

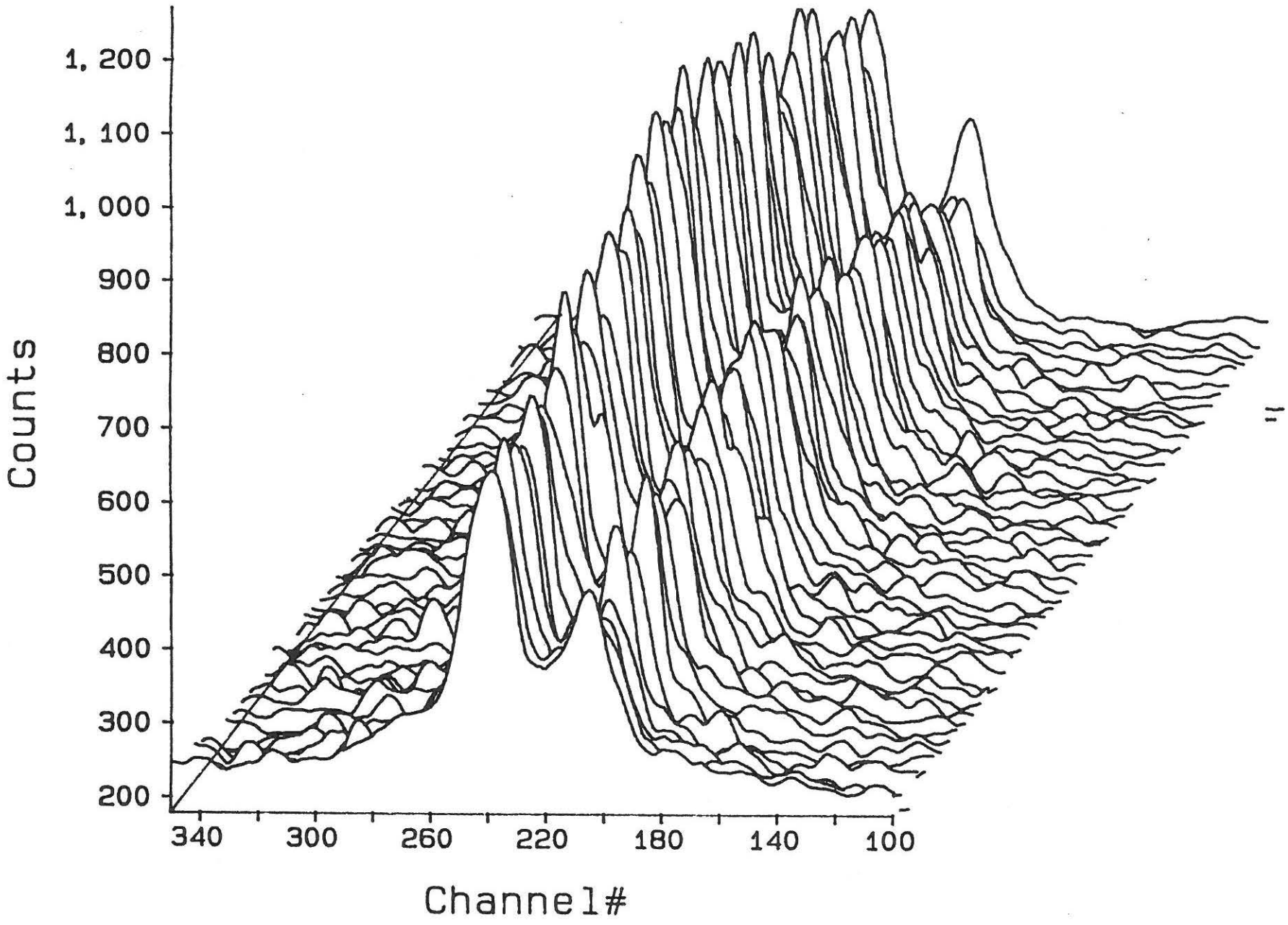
1, 200
1, 100
1, 000
900
800
700
600
500
400
300
200
Counts
340
300
260
220
180
140
100
Channel#

Fig. 4

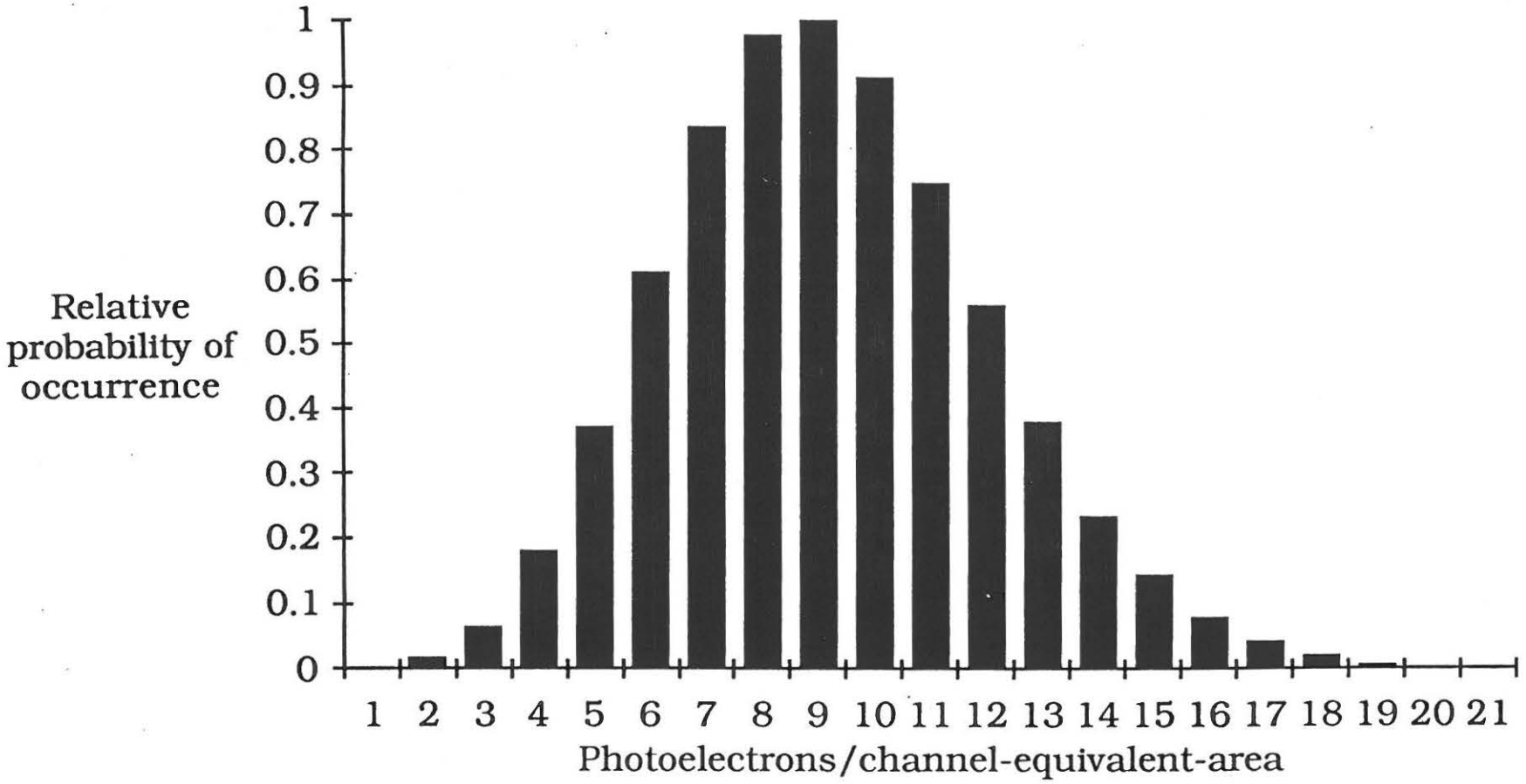
Relative probability of occurrence
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Photoelectrons/channel-equivalent-area

Fig. 5