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LASER INTENSITY MEASUREMENT

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LASER INTENSITY MEASUREMENTS

ABSTRACT

A method for obtaining laser intensity measurements has been developed and experimentally tested. A photographic plate is used to record the far-field laser intensity distribution. By using a multiple image technique the image is self calibrated. The computer program that processes the photographic density data produced by a scanning microdensitometer is also described. The program provides relative and absolute intensity distribution information. Data produced by this method are presented.

INTRODUCTION

Detailed laser intensity measurements are needed to compare theoretical calculations of laser produced plasmas with the experimental results. Hartman plate data, divergence measurements, burn patterns, lens interferograms, direct target photography, and far field cameras have been used to measure laser intensity. For some of these techniques, the assumption of spatial symmetry of the laser beam has been made, and where photographic methods have been employed, film calibration has proved difficult. A photographic method, which includes film calibration, and is applicable to any laser intensity distribution has been developed.

The method uses

- calorimetric measurements of the total laser energy
- photodiode measurements of the laser intensity as a function of time
- densitometer measurements of multiple image, far field patterns produced by an auxiliary lens

to obtain energy and intensity distributions on a laser target. Only the camera used to produce the far-field images is described in detail.

The major advantage of our technique is that the film is self-calibrating. The measurement of multiple images provides data for a density vs relative exposure curve for each plate at the time duration of the

laser radiation. This technique eliminates reciprocity effects when reducing the data. While the technique is not new, our implementation incorporates recently developed technology that allows us to measure arbitrarily shaped beam patterns.

An added advantage of the multiple image technique is that it produces an image of a desired density on a photographic plate even though the laser output varies from shot to shot. If the exposure of several images is adjusted so that the central image gives the proper exposure for the normal energy output, then the images on one side of this image will be overexposed while those on the other side will be underexposed. Should the laser output energy be higher (lower) than normal, one of the normally underexposed (overexposed) images will be the proper exposure. In this way, consistent measurements of the far field pattern can be made. Within any one shot, the overexposed images can be examined for details at the edge of the pattern while the underexposed images can be used for examining the center of the pattern.

The assumptions made in the use of this method are

- The power delivered by the laser can be calculated from calorimeter and photodiode measurements.
- Combining and weighting spatial data can be used to obtain the peak laser intensity.
- The relative spatial intensity distribution is not a function of time. For systems that exhibit whole beam self-focussing, this assumption is invalid.
- The camera is distortion free.
- The target is at the focus of the target lens.
- The intensity distributions at the focus of the target and camera lenses are the same except for size.

MULTIPLE IMAGE FAR FIELD CAMERA

In the measurement system developed for the Long Path Laser, the camera and target lenses are separate (Fig. 1). Our far field camera

Fig. 1. Long Path Laser intensity measurement system.

uses a grating to produce multiple images of different relative intensities. Our laser far field patterns are produced by an auxiliary lens. The number and relative intensities of the images are controlled by the grating.

The images produced by the grating have relative intensities related by a function of the form $(\sin x/x)^2$. Appendix A discusses the value of x for a grating. If the highest density image represents an energy E , then the other images represent fractions of E [the fraction is given by $(\sin x/x)^2$]. Within the highest density image, a particular spot has a density representing an intensity I' . In another image the same point has a different density which represents a fraction $(=\sin^2 x/x^2)$ of the intensity I' . The grating thus gives two pieces of information: (1) relative energies represented by each image, and (2) relative intensities of points within an image. The grating was photographically constructed by B. Herman of L Division's Technical Photography Group. A precision enlarged drawing of the grating was photographically reduced and reproduced on a photographic glass plate. Appendix A contains design information for gratings used as multiple image devices.

Specifications for our camera are shown in Table 1. We chose a long focal length lens to provide images large enough so that 100- μ details at the target would not be obscured by film granularity. The 6 x 14 cm elliptical laser beam set the lens and grating sizes. Previous experience with Kodak* I-Z plates caused us to fix the maximum ratio of known relative intensities at 20:1. This range also provides good calibration data when six to seven images are used. Theoretical values of the relative exposures produced by the grating are shown in Table 2. Since our grating is photographically produced, its damage threshold is low. We therefore rely on the sensitivity of hypersensitized I-Z plates to record the small fraction (~ 0.0016) of the total laser energy allowed to reach the grating. We have found it necessary to reduce this amount

* Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Atomic Energy Commission to the exclusion of others that may be suitable.

Table 1. Camera specifications.

Focal length	25 m
Grating	20 × 25 cm 1.71-mm period 0.23 mm clear space 7 images 20:1 maximum known intensity ratio
Shutter	Focal plane, 3-s exposure
Filter	Kodak Wratten; number 87, gelatin
Film	Kodak I-Z plates, 10 × 13 cm, hypersensitized

Table 2. Intensity ratios.

Grating order	Theory
0	1.00
1	0.94
2	0.78
3	0.57
4	0.34
5	0.16
6	0.05

further, depending on laser energy, by means of partial mirrors within the camera. Characteristics of the hypersensitized plates used here can be found in UCRL-75047 by Dittmore and Oonsar. We modified a speed graphic camera body for use as a plate holder and shutter. One multiple exposure photograph is taken for each laser shot by causing a solenoid to open the focal plane shutter for 3 s around the time the laser fires. A number 87 infrared filter in front of the shutter prevents flashlamp light from interfering with the exposure. It is necessary for room lights to be off during exposure.

DATA REDUCTION THEORY

Let the known relative intensities for each image be denoted by $\alpha(m)$ where m is the grating order producing the image. Then $\alpha(m) = I(m)/I(o)$, where $I(m)$ is the absolute intensity of the m th order image. Let the peak densities of each image vary by $D(m)$. The curve $\alpha(m)$ vs D then forms the conversion of photographic density to relative intensity.

To obtain the value of the peak intensity needed for conversion of relative values to absolute values, we use the fact that the sum of the product of the intensity within a certain area, $I(A)$, and the area, dA , is the power delivered in time Δt , $P(\Delta t)$, to the target. Mathematically,

$$\int_{\text{area}} I(A) dA = P(\Delta t).$$

Since the intensity anywhere in the image may be expressed as a fraction, $\alpha(A)$, of the peak intensity, I_p , we may write

$$\int_{\text{area}} \alpha(A) I_p dA = P(\Delta t).$$

This provides us with the value for the peak intensity

$$I_p = \frac{P(\Delta t)}{\int_{\text{area}} \alpha(A) dA}.$$

A discussion of the value used for $P(\Delta t)$ is found in Appendix B. The integral, quaintly called the "area of the peak," is a construction allowing calculation of the peak intensity as if the power delivered was deposited within that area.

The energy deposited within a given area, which has an intensity αI_p , is given by the product $\alpha I_p A$. We can then obtain the fraction of the total energy deposited in this region. Relative intensities

may be substituted for absolute intensities for this calculation. Another value indicating the distribution of intensity is the fraction of the total area that has a given intensity or relative intensity. Both of these distribution parameters (energy fraction or area fraction) are computed without regard to position with the target area. Frequency and cumulative frequency graphs can be produced to indicate these spatially independent distributions.

DATA REDUCTION — PRACTICE

Figure 2 illustrates the major steps in the flow of the data. The computer program INTENSITY has been written to reduce multiple image photographic density data. By reducing the data, we can obtain film calibration, the area of the peak, and the area and energy distribution of the intensity. The program also converts the original photographic density to relative intensity data that may be used by other data handling and display programs. A description of the preparation and digitizing of the photographic image is given in Appendix C. Appendix D contains details of the program and instructions on how to use it.

A sample calibration data and conversion curve, produced by INTENSITY, has been prepared for Long Path Laser data (Fig. 3). The calibration data lists the result of the computer search for density extremes in each image and the relative intensities to be associated with the maximum density. The images are identified by the grating order that produced the image. The position of the maximum density chosen by the computer is listed for each image to check that the same image point was chosen as the peak density for each image. The position values are not expected to match exactly since perfect alignment of the images on the densitometer is not required. The density discriminator is the density value below which a data point is assumed to represent noise and is excluded from calculations. The target-to-camera lens ratio used for a particular laser shot is also listed on the calibration page.

Fig. 2. Intensity data flow.

CALIBRATION DATA

PLATE ID : LPL 9. JAN. 74. PLATE 9

ORDER	MAXIMUM DENSITY	MINIMUM DENSITY	POSITION (LINE, POINT)		RELATIVE INTENSITY
0	1.365	0.165	72	69	1.000
1	1.290	0.150	33	94	0.940
2	1.145	0.140	72	62	0.780
3	0.955	0.130	63	64	0.570
4	0.655	0.115	65	63	0.340
5	0.305	0.040	63	63	0.160

DENSITY DISCRIMINATOR IS 0.132

TARGET TO CAMERA LENS RATIO IS 4.205798E-02

Fig. 3. Photographic calibration and conversion curve produced by the program INTENSITY.

The conversion curve, also shown in Fig. 3, results from a spline under tension curve fit to calibration points composed of the differences in the extreme density values and the corresponding relative intensity for each image. The points are plotted as O's. The curve is not used below the last data point.

Figure 4 shows the histogram, cumulative frequency, and relative intensity data produced by the program. The graphs represent the distribution of relative intensity in terms of the percent of the total image area having a given relative intensity value. The graphs and accompanying tables were calculated directly from the calibration points. The tables also present the intensity distribution with regard to the percent of the total laser energy deposited in a region which has a given relative intensity.

The figure also shows the area per data point, the total image area, and the number of image points. The area values are corrected to areas on the target by means of the ratio of the camera and target lens focal lengths. The final figures are two values of the conversion from relative to absolute peak laser intensity. Since the pulse duration and the fraction of the total energy delivered during that duration are, in general, unknown before the program is run, the reciprocal of the area of the peak is calculated by use of the conversion curve (the value marked "spline") and the calibration points (the value marked "histogram"). Multiplication of this value by the peak laser power yields the peak laser intensity and allows interpretation of relative values in terms of absolute intensity.

The cumulative frequency data were calculated so that the value along the y axis corresponds to regions where the relative intensity is at or above the corresponding value on the x axis.

The relative intensity image produced by INTENSITY contains the spatial intensity information lacking in the distributions shown in

Fig. 4. Relative intensity distribution data produced by the program INTENSITY.

Fig. 3. The programs listed in Appendix E can be used to process or display the intensity image. A photograph of a typical Long Path Laser multiple image camera plate is shown in Fig. 5. The density data from the densest image in the figure was used to produce Fig. 6. The conversion curve shown earlier was used to produce a relative intensity image (Fig. 7). The shelf at the base of the intensity image results from the special way in which low density data are handled (see Appendix D).

The multiple image self-calibration technique and data reduction programs have been useful in obtaining laser intensity information for experiments with the Long Path Laser. Results of some of these measurements are given in Appendix F. The program INTENSITY is applicable to any multiple image producing system, not just the grating system used here. With modification, INTENSITY could also be used to reduce single image photographs with calibration data produced by a step tablet rather than multiple images.

ACKNOWLEDGMENTS

My thanks to Jim Swain for suggesting the construction of the multiple image far field camera and allowing me the time to develop the program INTENSITY, to Joe Weaver for suggesting the use of gratings as multiple image devices, to Claude Dittmore for his invaluable microdensitometry, to Hank Finn for providing the display programs and the original program from which INTENSITY grew, and to Paul Renard and others who helped me through the development of INTENSITY.

Fig. 5. Photograph of a multiple image far field plate.

Fig. 6. Density isocontour and three dimensional representation of the densest image of Fig. 5.

Fig. 7. Relative intensity isocontour and three dimensional representations of the densest image of Fig. 5.

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APPENDIX A
DESIGN OF GRATINGS FOR MULTIPLE IMAGING

Grating Construction

The grating is photographically constructed. The parameters to be specified are the grating constant, d , and the grating clear space, a , as well as the size of the grating (Fig. A-1). The size of the grating should be at least the size of the lens.

To calculate d , we need to choose

- The number of images desired, $m_{\max} + 1$
- The focal length of the far field lens, f
- The space into which the multiple images are to fit, $x_{\max}$.

Then

$$d = \frac{(m_{\max} + 1) \lambda f}{x_{\max}},$$

where λ is the laser wavelength.

The number of images equals the highest order of the grating used ($m_{\max}$) plus the zero order. The focal length of the lens and the space into which the images will be placed are related by the width of the images ($\sim f \theta$, where θ is the full angle divergence of the beam) and the size of the photographic plate. If

$$\frac{\lambda f}{d} \gg f \theta$$

then the images will be separated from one another. The calculation for d ensured that the images would fit within $x_{\max}$ by requiring $m_{\max} + 1$ images to fit in the space $x_{\max}$. The method by which we pick trial values for f , $m_{\max}$, and $x_{\max}$ will depend on experimental conditions; i.e., plate size desired, image size, lenses available, etc.

To determine a , we choose the desired relative intensity range

Fig. A-1. Multiple image far field grating design parameters.

$$\frac{I_{m_{\max}}}{I_0} = \alpha(m_{\max}),$$

where, $I_{m_{\max}}$ is the peak intensity of the highest order image, I_0 is the peak intensity of the zero order image and $\alpha(m_{\max})$ is the desired ratio of these values. Then, since the ratio of the image intensities produced by the grating is given by

$$\left(\frac{\sin m\pi a/d}{m\pi a/d} \right)^2 = \frac{I_m}{I_0}$$

we find

$$\frac{\sin m_{\max} \pi a/d}{m_{\max} \pi a/d} = \frac{\sin m_{\max} y}{m_{\max} y} = \frac{\sin Z}{Z} = \sqrt{\frac{I_{m_{\max}}}{I_0}} = \sqrt{\alpha(m_{\max})}.$$

From the tables of $(\sin Z)/Z$, we find Z corresponding to $(\sin Z)/Z = \sqrt{\alpha(m_{\max})}$ before the first zero of $(\sin Z)/Z$ to ensure that none of orders ($m = 0$ to $m = m_{\max}$) will be "missing." Then $y = (Z/m_{\max})$ and $a = (yd/\pi)$.

Relative intensities of the images are then given by

$$\frac{I_m}{I_0} = \left(\frac{\sin my}{m y} \right)^2 = \alpha(m).$$

Before constructing the grating, we should consider the spectral dispersion of the grating since it may degrade the spatial resolution of the far field patterns. The maximum spectral dispersion is given by

$$\frac{\Delta\lambda}{\lambda} = \frac{d}{m_{\max} f},$$

while the maximum spectral resolution of the grating $\Delta\lambda_G$ is given by

$$\Delta\lambda_G = \frac{\lambda d}{W m_{\max}},$$

where W is the width of the laser beam perpendicular to the grating lines; i.e., the width of the grating intercepted by the laser. If the laser spectral bandwidth, $\delta\lambda_L$, is such that $\delta\lambda_L < \Delta\lambda_G$ then the minimum spatial resolution of the images is given by

$$\frac{\frac{\Delta\lambda_G}{\Delta\lambda}}{\frac{\Delta\lambda}{\Delta x}} = \frac{f\lambda}{W} \quad (\text{Laser bandwidth less than grating resolution})$$

If $\delta\lambda_L > \Delta\lambda_G$ then the minimum spatial resolution is

$$\frac{\delta\lambda_L}{\frac{\Delta\lambda}{\Delta x}} = \frac{m_{\max} f}{d} \delta\lambda_L \quad (\text{Laser bandwidth greater than grating resolution})$$

Note the zero order is devoid of such problems since $\Delta\lambda/\Delta x = \infty$ for $m = 0$, while the maximum order will have the worst spatial resolution.

Another consideration should be the distortion in the intensity profile of a particular image caused by the $(\sin x/x)^2$ envelope of the grating. This may be assessed by comparing $f(m)\left(\frac{\sin my}{my}\right)^2$ to $f(m)\left(\frac{\sin ny}{ny}\right)^2$, where $f(m)$ is the true intensity profile of the image expressed in terms of the variable m (the order of the image), and n is the particular order under investigation. The constant y is $\pi a/d$ for the grating. Distortion of this kind is least for the zero order image and greatest for the highest order image.

A calculator program for the HP 9810A calculator has been developed to aid in the design of a grating. A sample output from the program is shown in Fig. A-2. Values with an asterisk behind them were values supplied to the program. The values listed are λ , f , $x_{\max}$, $m_{\max}$, d , x_m , $\alpha(m_{\max})$, A , Y , a , $\alpha(0)$ through $\alpha(m_{\max})$, $\Delta\lambda/\Delta x$, w , and $\Delta\lambda$. The values correspond to the parameters used for the Long Path Laser. All values are in mm except the dispersion and resolution which are in $\text{\AA}/\text{mm}$ and $\text{\AA}$, respectively. The 9.999 98 figure for $\alpha(0)$ results from the computer's inability to calculate $\sin 0/0$.

	Z =	2.53809
	Y =	0.42301
GRATING DESIGN	CLEAR SPACE =	0.23083
WAVELENGTH (MM) =	INTENSITY RATIOS	
0.00100*	ALPHA (M)	
FOCAL LENGTH =	9.999999999 98	
24490.00000*	0.94176	
DISTANCE =	0.78305	
100.00000*	0.56609	
MAX ORDER =	0.34417	
6.00000*	0.16360	
GRATING CONSTANT	0.05000	
=	1.71430	
IMAGE SEPARATION	MAX DISPERSION	
=	116.66667	
14.28571	BEAM WIDTH=	
MAX INTENSITY RA	140.00000*	
TIO =	MAX RESOLUTION	
0.05000*	20.40833	

Fig. A-2. Output of the grating design program.

For this example, the sixth order image will have the most grating-induced distortion. Figure A-3 illustrates this distortion for a gaussian image whose FWHM is 0.3 of the distance between orders (or images). The effect of the grating on the sixth order image is seen as a skewing of the profile and a peak intensity somewhat greater than that calculated peak $\left(\frac{\sin 6y}{6y}\right)^2$. The program INTENSITY converts the zero image to relative intensity, thus minimizing the distortion problem.

Notes on Formula Derivations

The proper grating equation is

$$m\lambda = d \sin \beta,$$

where β is the diffraction angle and α , the angle of incidence, is zero.

The approximation $\sin \beta \cong \tan \beta \frac{x}{y}$ has been used to obtain the formulas for d and $\frac{\Delta\lambda}{\Delta x}$.

Fig. A-3. Grating induced image distortion for the sixth order image.

APPENDIX B CALCULATION OF LASER POWER

For $P(\Delta t)$ we can compute $E_{\text{total}}/\Delta t$, where Δt is the FWHM duration of the pulse and E_{total} is the energy measured by a calorimeter. If we assume $P(t) = \cos^2 \pi t/2\Delta t$ and compute the ratio of energy delivered in time Δt [$E(\Delta t)$] to the total energy delivered, we find only 82% of the energy is delivered between FWHM points. For gaussian pulses, only 76% of the energy is delivered between FWHM points. To avoid making an error of that size and realizing most pulses are not symmetrical, we calculated $P(\Delta t)$ by integrating a photodiode or streak camera trace of the laser pulse. We also determined the ratio of the total power to the power delivered between the FWHM points. The value for $P(\Delta t)$ then becomes $P(\Delta t) = \frac{\xi E_{\text{total}}}{\Delta t}$, where ξ is given by

$$\xi = \frac{\int_{-\frac{\Delta t}{2}}^{\frac{\Delta t}{2}} P(t) dt}{\int_{-\infty}^{\infty} P(t) dt} = \frac{\int_{-\frac{\Delta t}{2}}^{\frac{\Delta t}{2}} \beta(t) P_p dt}{\int_{-\infty}^{\infty} \beta(t) P_p dt} = \frac{\int_{-\frac{\Delta t}{2}}^{\frac{\Delta t}{2}} \beta(t) dt}{\int_{-\infty}^{\infty} \beta(t) dt},$$

where $\beta(t)$ is the fraction of the peak power delivered at time t .

A computer program that may be used with the HP9810A calculator and the HP digitizer has been written. By examining an oscilloscope or densitometer trace, we can directly calculate (using the program) the FWHM and the fraction ξ of the total energy delivered between the FWHM points. Because most oscilloscope traces are small, it is desirable to have an enlargement of the photograph made when possible. The program allows for rotation and translation of the photograph axes, and scaling of the time axis. Typically for the Long Path Laser, 0.78 to 0.80 of the total energy is found to be delivered to the target between the FWHM points by this method.

APPENDIX C
MICRODENSITOMETRY

C. Dittmore of L-Division's Technical Photography Group is using a PDS scanning microdensitometer to digitize the photographic density data used by INTENSITY. A PDP 11/20 computer controls the densitometer and stores the data on 556 or 800 bits per inch (BPI) 1/2-in. magnetic tape.

The information needed to digitize a photograph is shown in Table C-1. A copy of this table is included with each photograph for use during digitizing. Generally it is best to zero the densitometer on base plus fog even though INTENSITY also does a search for, and subtraction of, a base level. The multiple images must be scanned starting with the densest image (zero order). The images are therefore marked by their order number (0 thru 5 or 6) and scanned in that order. Either a raster or edge scan mode may be used since subsequent data processing takes the type of scan into account. Digitizing intervals (x step and y step in Table C-1) of 70 μ have been used for most Long Path data since this yields a data point for each 9 μ^2 at the focus of an f/8 lens (the target area is usually near $6 \times 10^4 \mu^2$). The present limit of 500 data points per scan line in the program INTENSITY may be a limiting factor in the size of the digitizing interval when large areas are scanned. The additional limit of film granularity also must be considered when selecting a digitizing interval. The total distance to be digitized (times travel and number of scans) is chosen so that all of the image plus an amount of nonimage background will be included in the scan. The number of scans

Table C-1. Densitometer information

Zero on base	_____
x step	_____ x travel
y step	_____ Number of scans
IDENT	_____

is y step divided into the total y distance desired. The IDENT is a 40 character identification label that will be attached to all multiple image data sets and will identify the output of INTENSITY. A typical identification might be: LPL.25.Jan.74.SHOT.2..465J. Note the blanks are not allowed so periods are used in their place. The identification is not used for data purposes so any convenient form can be used.

Since the computer run densitometer is sensitive, poor quality or scratched photographs will yield poor or unusable data. Digitizing six images of 1 cm on a side in 70- μ steps takes about 20 min. Care should be taken in selecting photographs so that valuable densitometer time is not lost.

APPENDIX D COMPUTER PROGRAM INTENSITY

The major steps in the program INTENSITY are shown in Fig. D-1.
The inputs to the program are:

- Data files containing multiple image density information produced by the PDS densitometer.
- Calibration factors for image area and relative intensity.
- The name of the relative intensity image to be produced.

With the exception of nonstandard calibration data, all input information is entered on the execute line:

INTENSITY cal name1 name2 / t v,

where cal is LPLn (n = 0, 2, 4, or 8) or ASK, name1 is the first name of a sequence of data files containing the multiple image density information, and name2 is the name of the relative intensity image to be produced by the program.

LPLn selects the internally stored calibration factors shown in Table D-1. The ASK option causes the relative intensity calibration factors and the lens focal length ratio to be requested. The lens focal length ratio is in E14.6 format and may be terminated by a comma (i.e., "4.07E-2,"). The first data file name (name1) should end in 1 and the last should be less than 8 (i.e., A1 through A7). There are no restrictions on the name of the intensity image. Figure D-2 shows two examples of teletype input and output for INTENSITY.

Table D-1. LPL calibration factors

Relative Intensities	Lens ratios
1.00	LPL 0 1.0
0.94	
0.78	LPL 2 1.242×10^{-2}
0.57	
0.34	LPL 4 2.484×10^{-2}
0.16	
0.05	LPL 8 4.025798×10^{-2}

Fig. D-1. Flow chart for the program INTENSITY.

INTENSITY LPL8 D1 ID / 1 1
PLATE ID : LPL.12.DEC.73.SHOT.1..17.3J

RECIPROCAL AREA OF THE PEAK IS 8.54577E+03
LPL#, ASK, OR END, DENSITY ROOT AND INTENSITY FILE NAMES
END

ALL DONE

INTENSITY ASK B1 IB / 1 1
CALIBRATION FACTORS

AI(0) = ?

1.

AI(1) = ?

.78

AI(2) = ?

.57

AI(3) = ?

.2@34

AI(4) = ?

.16

AI(5) = ?

.0

AI(6) = ?

.000

FOCAL RATIO OF THE LENSES ?

4.025798E-02,

PLATE ID : LPL.12.DEC.73.SHOT.5..27.7J

%S RUN +INTENSITY

%U 0002.0658

%? R05/20 11.25:01 0000.6559 RUN +INTENSITY

RECIPROCAL AREA OF THE PEAK IS 1.31444E+04
LPL#, ASK, OR END, DENSITY ROOT AND INTENSITY FILE NAMES
END

ALL DONE

Fig. D-2. Teletype input and output examples for the program INTENSITY.

INTENSITY produced a DD-80 output file called DAUTOCAL $\underline{n}$ $\underline{m}$ where $\underline{n}$ may be A through Z and $\underline{m}$ may be zero through 9 or X. If only one density data set is run and the program is terminated, the name is DAUTOCALAX. The next run of the program will produce DAUTOCALBX. If multiple runs are made without termination of the program, the name will be DAUTOCALAX. An abnormal termination of the program results in DAUTOCAL $\underline{n}$ Y.

Once calibration data and file names have been specified, each density file is averaged and searched for the maximum and minimum density values in the averaged image. The averaging process is an attempt to prevent the selection of the maxima from influence by dust on the image. All data processing after this initial search for extrema is done with nonaveraged data. INTENSITY searches for data files with the name $\underline{\text{name1}} + \underline{m}$, where $\underline{m}$ is less than seven. The absence of a file indicates all images for that data set are done and the program proceeds to convert the densest image to relative intensity, find the distribution of intensity, and calculate the area of the peak used to calculate the peak laser intensity.

The source program for INTENSITY is PDSJ32. It is a modified version of LINEOUT (PDS3), which was written by H. Finn. The subroutines and functions in INTENSITY are listed in Table D-2. The main part of the program handles the conversion factors, the creation of the intensity file, and the opening of the data files.

The subroutine HISTOGRAM carries the main work load in the program. From the density extremes for each image, a calibration density is calculated from the difference of the extreme values. The calibration densities are paired with the calibration relative intensities and passed to the subroutine TSPLINE, which creates the photographic density to relative intensity conversion curve. The difference in extreme density values for an image was chosen as the calibration density to remove the effect of a rising base density often seen from one image to the next in multiple image photographs. TSPLINE constructs a curve through the calibration points using a spline fit under a variable tension. The tension is

Table D-2. PDSJ32 subroutines.

MAXMIN	- finds the maximum and minimum density of an averaged file
GETMAXAV	- obtains a 25-point running average of a file for MAXMIN
HISTOGRAM	- produces relative intensity distribution data, the peak intensity, the intensity image, and the DD80 output file
TSPLINE	- creates a spline under tension through the intensity calibration points
TOFRO	- creates the coefficients of the spline under tension
VALUE	- provides relative intensity from density using the spline under tension

internally adjusted so that there are no negative slopes in the conversion curve. The conversion curve is not valid below the lowest calibration density so special handling is provided for densities less than that value. First, a discriminator equal to half the lowest calibration density is calculated. Any density below the discriminator is assumed not to be a part of the image and is given the relative intensity zero. Density values above the discriminator but below the lowest calibration density are assigned a relative intensity of half the value associated with the lowest calibration density. This procedure results in the appearance of a shelf or bench of height 0.08 or 0.025 of the peak intensity for Long Path data. After subtraction of minimum density in the densest image from a data point in that image, the conversion to relative intensity is made and this converted point becomes a part of the intensity image. An integration of the relative intensity values and a sorting of the values is also done so that the peak intensity and the intensity distributions as functions of energy and area can be calculated. The reciprocal area of the peak is sent to the teletype at the end of the program along with a request for new input data. Run time is about 0.1 min for each 150 by 150 point image.

Because of the type and amount of data in a single data file, all the data cannot be stored in an array. For this reason a scan line at a time is usually read from the data for processing. In addition, PDS

computer words are ten bits long and are packed so that six of them compose each 60-bit DCD 7600 computer word. All PDS data handling programs use coded density data. To use these routines, the intensity data is coded as if it were density information. Hence, the relative intensity 1.0 is stored in the intensity file as the value 200.

For the present (June 1974) two programs must be run to prepare PDS data for INTENSITY. TAPECOPY is a utility routine that copies the PDS data from magnetic tape and names the image files. UNSCRAMBL is a PDS program that repacks the PDS data. All other PDS programs and INTENSITY use the packed data. These two routines are to become obsolete soon because the naming and repacking of image files will be done by the PDS densitometer PDD 11/20 computer. The instructions which follow for TAPECOPY and UNSCRAMBL are temporary and C. Dittmore should be consulted when the UNSCRAMBL is no longer needed.

For the use of TAPECOPY, the record length (RL), buffer length (BL), and octal length (OL) for the files must be specified:

RL = ((NPTX*24) + 672)) /60 rounded up
BL = 60 * RL rounded up
OL = NLIN * RL converted to base 8
NPTS = the number of points per PDS scan
NLIN = the number of scans in the image.

Items that are in parenthesis below are messages sent by the program. The execute line is

```
TAPECOPY RL BL / t v  
(ok)  
tapename 1 filename Ø (U) n m  
(options or linefeed)  
FAM.  
(ok)  
END  
(type octal length of the file to be created)  
OL
```

tapename is the vault number of the tape which contains the
 PDS data
filename is the name of the first file read from tape
n is the number of the first file to be read (i.e., 1)
m is the number of the last file to be read (i.e., 6)

FAM. causes TAPECOPY to create $m - n + 1$ files with the names filename^0^
 0^1 through filename^0^0^($m - n + 1$). END refers to the end of the options.
 After the files have been read, TAPECOPY asks for END or options. If
 another data set is to be read, specify the option "FAM. filename" and
 then type 0 filename m s U o 1. This asks for another output file (0)
 with name filename to be copied. m is the number of files to be copied,
s is the number to skip before starting to copy, and U means the file
 is unformatted.

UNSCRAMBL expects an input file from TAPECOPY and produces an output
 file to be used by INTENSITY or another PDS program. UNSCRAMBL is con-
 versational. Both programs may be run by PROXY to cut down interaction
 time.

APPENDIX E
DATA REDUCTION AND DISPLAY PROGRAMS

H. Finn of L Division has written computer programs for manipulating and displaying the data produced by the PDS densitometer. Details on the use and output of these programs is given in DAG 74-4/TP 74-1 and DAG 73-32/TP 73-22.

A list of the programs which may be used on INTENSITY created data is given here.

<u>Program</u>	<u>Use</u>
DISPLAYIT	Provides three-dimensional and iso-contour display
LINEOUT	Provides single scan line plot
EXCERPT	Extracts a portion of the data for further analysis or display
HISTOGRAM	Provides the frequency of occurrence for intensity as a function of area (This is a subroutine of INTENSITY)
SMOOTHIT	Smooths the data by taking a five point by five line running average of the data
LINEAVG	Averages all scan lines into one scan line

In addition, the L-Division program SOCKITTOME is available for data manipulation of line data.

APPENDIX F LONG PATH LASER INTENSITY MEASUREMENTS

The data presented here were taken from the Long Path Laser target interaction experiments. The computer program INTENSITY was used to obtain the area of the peak and the intensity distributions.

Table F-1 shows data from three shots on which x-ray measurements were being made. The ratio of target lens and camera lens focal lengths was 4.2058×10^{-2} . The reciprocal area of the peak has been corrected to the target by this factor. The energy listed is about 80% of the total energy delivered and corresponds to that delivered in the FWHM pulse durations listed. Both values were determined from oscilloscope traces of the pulse intensity. The intensities are typical of the Long Path Laser.

Table F-2 is a list of energies, total areas, and the resulting intensities for 27 laser shots. Means, standard deviations, and standard deviations of the mean as well as the extremes are also listed. The time duration is a constant, 4×10^{-9} s. (The standard deviations are measures of the scatter of the data about the mean value while the standard deviation of the mean is a measure of the scatter of the mean values to be expected if the experiments were repeated many times.)

A graph of the intensity of each laser shot vs the energy for that shot is given in Fig. F-1. The average is plotted as an A while the average plus and minus one standard deviation is plotted with an S. Figure F-2 displays the relation of the total area for a shot and the energy of that shot. The same notations are used as in Fig. F-1.

Table F-1. Long Path Laser intensity.

Reciprocal of peak area (10^3 cm^{-2})	Energy (J)	FWHM pulse duration (10^{-9} s)	Intensity (10^{13} W/cm^2)
4.779	24.96	5	2.3
5.007	33.54	4	4.2
3.023	20.80	4	1.6

Fig. F-1. Intensity vs area for the data of Table F-2.

Fig. F-2. Area vs energy for the data of Table F-2.

Table F-2. Laser energy and intensity and target area.

	Energy (J)	Total area (10^{-4} cm ²)	Intensity (10^{13} W/cm ²)
	31.4	6.5	4.2
	29.6	8.9	3.9
	16.5	4.7	4.5
	19.5	6.6	1.8
	22.7	8.9	3.9
	26.9	6.7	5.8
	33.5	7.5	4.8
	33.8	8.1	4.6
	26.0	10.0	2.0
	29.7	8.9	2.5
	24.3	13.0	3.6
	28.2	9.5	2.6
	29.9	11.0	4.4
	21.5	7.5	2.5
	28.9	9.6	2.5
	23.2	6.1	3.0
	26.1	7.5	6.1
	16.1	2.7	6.3
	29.9	13.0	2.3
	29.1	5.1	5.2
	32.7	4.7	6.9
	28.3	7.2	7.0
	34.2	9.9	3.1
	37.8	9.0	4.6
	47.4	4.4	6.1
	46.0	11.0	4.2
	16.9	14.0	3.3
Averages	28.52 J	8.22×10^{-4} cm ²	4.14×10^{13} W/cm ²
Standard deviations	7.66	2.77×10^{-4}	1.52×10^{13}
Standard deviations of the mean	1.47	5.35×10^5	2.93×10^{12}
Extreme	16.1	2.7×10^{-4}	1.8×10^{13}
Values	47.4	1.4×10^{-3}	7.0×10^{13}

Note in Table F-2 that low energy and small total area are coupled as are high energy and large total area. This reflects the increase in divergence of the laser beam with increasing energy and is a major reason why the Long Path intensity is weakly dependent on energy.

A frequency distribution for the average energy deposited in a region of the target, which has a given relative intensity range, is shown in Table F-3 and displayed in Fig. F-3 along with a least squares fit of the data to a parabola. The frequency distribution may be approximated by:

$$E/E_T = -0.94 (I/I_p)^2 + 0.89 (I/I_p) + 0.07,$$

where E/E_T is the fraction of the total energy deposited in a region with an average relative intensity of I/I_p . This indicates 11% of the energy is, on the average, deposited in regions whose relative intensity is near 0.9% of the peak intensity.

A cumulative frequency distribution for the average fraction of the total energy deposited in target regions with relative intensities at or above a given relative intensity is shown in Table F-4 and displayed in Fig. F-4 along with a least squares fit of the data to a parabola. The cumulative distribution may be approximated by

$$(I/I_p) = 0.76 (E/E_T)^2 - 1.66 (E/E_T) + 0.97,$$

where I/I_p is the relative intensity and E/E_T is the fractional energy. Both the figure and the table show that half the energy is deposited, on the average, in regions with relative intensities above 0.33.

Table F-3. Average energy frequency distribution for 17 data points.

Relative intensity range	Average fractional energy	Standard deviation
0.94 - 1.00	0.034	0.017
0.78 - 0.94	0.066	0.034
0.57 - 0.78	0.149	0.063
0.34 - 0.57	0.281	0.070
0.16 - 0.34	0.282	0.084
0.05 - 0.16	0.168	0.101

Fig. F-3. Average energy distribution.

Fig. F-4. Average cumulative energy distribution.

Table F-4. Average energy cumulative frequency distribution for 17 data points.

Relative intensity	Average fractional energy	Standard deviation
1.0	0.0	- ^a
0.94	0.034	0.017
0.78	0.100	0.043
0.56	0.250	0.094
0.34	0.530	0.135
0.16	0.810	0.135
0.05	0.926	0.032

^aData without standard deviations are known data points.

Table F-5. Average area frequency distribution for 17 data points.

Relative intensity range	Average fractional area	Standard deviation
0.94 - 1.00	0.007	0.003
0.78 - 0.94	0.017	0.013
0.57 - 0.78	0.070	0.057
0.34 - 0.57	0.152	0.068
0.16 - 0.34	0.268	0.107
0.05 - 0.16	0.381	0.050
0.0 - 0.05	0.0	- ^a

^aData without standard deviation are known points.

A frequency distribution for the average fraction of the total area of the target, which has a relative intensity in a given range, is shown in Table F-5 and displayed in Fig. F-5 along with a least-squared-fit of the data to a parabola (solid curve) and a hand-drawn fit. The least-squares fit is unacceptable; the hand-drawn curve at least fits the data. The large scatter of the data at high relative intensity suggests that a small fraction (near 1.0%) of the area of the target has a relative intensity between 0.94 and 1.0 of the peak intensity.

A cumulative frequency distribution for the average fraction of the total area of the target, which has a relative intensity at or above a given relative intensity, is shown in Table F-6 and displayed in Fig. F-6 along with a least-squares-fit of the data to a parabola. The

Fig. F-5. Average area distribution.

Fig. F-6. Average cumulative area distribution.

least-squares fit is not a pleasing one; the dotted curve is hand-drawn and is probably closer to the true curve - if one exists. The data shows on the average 10% of the area has an intensity above one-half the peak intensity.

Table F-6. Average area cumulative frequency distribution for 17 data points.

Relative intensity	Average fractional area	Standard deviation
1.0	0.0	-
0.94	0.007	0.003
0.78	0.028	0.016
0.57	0.084	0.048
0.34	0.238	0.108
0.16	0.505	0.189
0.05	0.614 ^a	0.066
0.0	1.0	- ^b

^aRepresents 5 data points.

^bData without standard deviations are known data points.

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