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Particle field holography data reduction by Fourier transform analysis

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Abstract

The size distribution of a particle field hologram is obtained with a Fourier transformation of the Fraunhofer diffraction pattern of the reconstructed hologram. Off-axis absorption holograms of particle fields with known characteristics were obtained and analyzed with a commercially available instrument. The mean particle size of the recon-structed hologram was measured with an error of ±5%, while the distribution broadening was estimated within ±15%. Small sections of a pulsed laser hologram of a synthetic fuel spray were analyzed with this method thus yielding a spatially resolved size distribution. The method yields fast and accurate automated analysis of particle field holograms.

Introduction

Pulsed laser holography has been a very powerful technique to charac-terize particle fields in complex environments. Examples are studies of pulverized coal combustion[1], fuel sprays[2], and explosions[2]. However, its use has been restricted because of the tedious effort required to

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reconstruct and analyze particle field holograms. The analysis of holo-
grams has been performed by taking photographs at various planes of
interest and then analyzing the photographs in computerized image analy-
zers. This suffers from various shortcomings. The most important are:
photographic images have associated depths of field which lead to size
errors; the process, even though more automated than the more primitive
visual analysis, is still tedious. Recently, a technique using
Fraunhofer diffraction analysis was introduced[3]. This technique bases
the size measurement in the Fourier transform analysis of the light dif-
fracted by an ensemble of particles illuminated by a laser beam. The
direct analysis of a particle field with such method has been used quite
extensively[4]. The logic proposed in reference [3] is that since the
Fourier transform of the Fraunhofer diffraction pattern of an ensemble
yields the size distribution, such transformation will also yield the
size distribution if the particles are substituted by a particle field
hologram.

This technique was tested[3] in connection with on-line holograms, and
its application was illustrated[5] in the measurement of pulsating fuel
sprays. There are, however, problems associated with reconstructing on-
line holograms such as deterioration of the reference beam and confusion
between the real and virtual images.

The approach chosen by the authors and discussed in this paper was to
use off-axis holography in conjunction with Fourier transform analysis.
Particle fields of known characteristics were measured and compared.
The results show that for Rossin Rammler size distributions the mean
size was predicted very accurately (±5%), while larger errors were

experienced in the broadening parameter (±15%). Some of these errors and inconsistencies were associated with instrument alignment and extraneous noise which, for the most part, can be eliminated, primarily by increasing the diffraction efficiency of the holograms.

The interface of pulsed laser holography with a Fourier transform analyzer of the diffracted light will greatly extend the capabilities of both. The former will benefit from fast almost-in-line data reduction. The later which is a much slower process when used in conjunction with holography will provide data unattainable until now. Examples are particle sizing in turbulent combustion phenomena, where beam steering is a problem associated with light scattering techniques; explosions, where the events take place in microseconds; and time dependent sprays or other particle laden flows where it is of interest to resolve the time variation of the particle field distribution.

Theoretical Discussion

The amplitude scattered by a particle of radius a through an angle β is given by

$$A = \frac{A_i a J_1(ka\beta)}{\beta} \tag{1}$$

where A_i is the illuminating amplitude

J_1 is the Bessel function of the first kind, and

$k = 2\pi/\lambda$ and it is assumed that

$a >> \lambda$ the wavelength of light.

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If a distribution of particle sizes f(a) exists, then the contribution by those of size between a and a + da is to the amplitude at an angle β is

$$\frac{f(a)da \; aJ_1(ka\beta)}{\beta} \tag{2}$$

and the total amplitude in that direction is

$$A_t = \frac{A_i}{\beta} \int_0^\infty f(a)a \; J_1(ka\beta)da \tag{3}$$

What is sought in particle sizing measurement is f(a) which is given by[6]

$$f(a) = \frac{-2}{ka} \int_0^\infty \beta J_1(ka\beta)Q(\beta)Y_1(ka\beta)d\beta \tag{4}$$

where Y_1 is the Neumann function and

$$Q(\beta) = \frac{d}{d\beta}\left[\pi k^3\beta^3 \frac{I}{I_o}\right] \tag{5}$$

The above expression has been approximated numerically and is the basis for particle sizing instruments based on a measurement of the angular spectrum of scattered light. There is a one-to-one correspondence between the angular spectrum and the Fourier transform of the scattered light, and the latter is what is usually measured.

If the wavefront scattered by the collection of particles is stored in a hologram as an intermediate step and reconstructed later for analysis, it becomes of concern how the ultimate wavefront may differ from the original one.

The hologram can be represented by a transfer function. The amplitude of light reconstructed from the hologram can be written[7] (using only one of the two dimensions)

$$A_t(\beta/\lambda) = A_i(\beta/\lambda) * T(\beta/\lambda) \tag{6}$$

where

$$T(\beta/\lambda) = \int_{-\infty}^{\infty} t(y) \exp\left[j2\pi\frac{\beta}{\lambda}y\right] dy \tag{7}$$

The convolution has characteristics which can both narrow and broaden the spectrum. If the hologram is too small, then the spectrum will be broadened by its own diffraction. If it is large and perfect, then T is effectively unity. In practice, the transfer function, T, is more likely to decrease gradually with β as the film MTF decreases with

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frequency. The effect is to bias the distribution of f(a) to larger particles. These above relations show that with good practice the data derived with holography as an intermediate step can accurately emulate that using the Fourier Transform directly, and they could be used to correct for holograms not having a unity transfer function.

Experimental approach

The approach chosen in this study was that of comparing the size distribution obtained by analyzing a known particle field with that of a hologram of the same particle field. To simplify the experiment, the particle field chosen was stationary thus allowing the use of a cw He-Ne laser for the acquisition of the hologram. The Fourier transformation was performed by a Malvern 2600 particle analyzer. A description of the apparatus and particle fields is now given.

Holographic system

The holographic system was a breadboarded, off-axis, through field system, having separate object and reference beams, as seen in Figure 1. The object beam was disturbed by a particle field, while the reference beam was undisturbed. The two beams interfere when they overlap on a holographic film plate.

A 25 mW Helium Neon Laser (Spectra Physics Model 107) was used as the illumination source. The beam was split with an uncoated glass beam-splitter (Newport Corporation #20B10NC.1). A split ratio of 4:1 (reference to object beam) was chosen to provide good reconstruction

efficiency while remaining in the linear region of the film. The ratio was adjusted by varying the angle of incidence to the beamsplitter, thus changing the reflectivity.

The reference beam was expanded using a 5x microscope objective and spatially filtered with a 40 micron pinhole. It was collimated by a 380 mm focal length achromatic lens and apertured to a 10 mm diameter nearly uniform intensity beam. The collimated reference beam was then directed to the holographic plate, where its peak intensity was measured at 28 $\mu w/mm^2$.

A 10x microscope objective and a 25 micron pinhole were used to expand and filter the object beam. An achromatic collimating lens, with a 125 mm focal length, produced a Gaussian object beam with a diameter of 10 mm ($1/e^2$). The object beam illuminated a particle field which was imaged on the holographic plate by 1:1 magnification lens system. This imaging system consisted of two 50 mm Olympus Lenses positioned back-to-back, connected by bellows. It collected the forward scattered radiation and the unscattered radiation and relayed them to the holographic plate. The object beam peak intensity was measured to be 6.4 $\mu w/mm^2$.

The Fourier Transform Analyzer

The receiver of a Malvern 2600 was used to collect and analyze the Fraunhofer diffraction field. A Fourier transform lens, in the receiver, collects both the forward scattered and unscattered radiation and focuses it onto a concentric photodiode array. The scattered radiation is transformed to a series of diffraction rings at the focal plane of the lens. Thirty concentric half-ring diodes receive these data

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which are transferred to a minicomputer for processing. The unscattered radiation is focused on a pinhole at the focal plane of the receiving lens. This radiation illuminates a separate diode, indicating the amount of unscattered radiation.

Figure 2 shows a photograph of the holographic system interfaced to the Malvern receiver which is interfaced to a microprocessor based data reduction system. The holographic recording/reconstruction system was designed to produce holograms capable of simulating the Malvern transmitter beam illuminating a particle field.

Particle fields

Two particle fields were used throughout these experiments. The first was a calibration photomask (Laser Electro-Optics Ltd.[8] #RR 50-3.0-0.08-102.CF) which contains a known size distribution of circular particles. The second was a particle field hologram of a spray of synthetic fuel (SRCII) acquired in a previous program using a pulsed laser holographic system.

The photomask was chosen for two primary reasons:

1. It provided a known and stationary particle field of which holograms could be taken with a cw laser.
2. Both the photomask and holograms of the photomask could be analyzed and compared against an absolute invariable distribution.

The calibration standard photomask consisted of a 2-dimensional sample array of 10,000 circular discs of chrome deposited on a glass substrate. The discs are randomly oriented in an 8 mm diameter sample area. The photomask contains a Rossin Rammler size distribution with $\overline{X}$ = 50 μm and a width parameter of 3.0 (Figure 3).

The particle field hologram described here containing a synthetic fuel spray was taken previously using a pulse ruby laser holocamera. The receiving optics provided a premagnification of 3:1. It has previously been determined, through existing reconstruction techniques, that the mean size of the spray droplets in this hologram lies in the range from 50 to 100 μm (depending on location) which will be interpreted as 150 to 300 μm on the magnified image of 3:1.

Procedure to align the Malvern receiver

The reconstructed image of the hologram must be collected by the receiving lens (we used the 300 mm in all the tests) and focused on the diode array. Since the receiving lens of the Malvern has no focus adjustment, it is important that the reconstructed unscattered radiation be collimated and, therefore, produce a sharp focus on the hole in front of the center diode.

The receiver was then steered until its optical axis was parallel to the reconstructed unscattered lighty. It was then translated vertically and horizontally until the light beam entered through the center of the lens.

The final fine adjustments were made with the adjustment screws of the receiver.

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Signal level requirement

We established that the radiation power of the reconstructed holographic image was typically between .15 mw and .25 mw. This can be obviously increased using a more powerful laser or increasing the diffraction efficiency of the hologram (using phase holograms). Since the Malvern apparatus uses a 2.5 mw laser, we had to establish the performance of the photodiode array at low power. The procedure consisted in illuminating the photomask with different levels of laser power. For this purpose, a variable neutral density filter was placed in front of the laser such that the total power of the light incident on the receiver varied between 50 µw and 2.5 mw. Under each one of these laser power levels we obtained a size distribution using the Rossin Rammler and the model independent softwares. Power levels of 100 µw and more produced the same size distribution of the photomask. Power levels below 50 µw were not acceptable. It was also necessary, in order to work with the low power levels, to darken the room to reduce background radiation. Based on these results, it was expected that the typical 150 µw signal obtained from the reconstructed image would be adequate. Let us point out again that higher signal levels could be attained by reconstructing with a more powerful laser or by producing more efficient holograms. Obviously, increasing the diffraction efficiency without compromising the linearity would be the preferred choice since part of the noise comes from scatterers on the emulsion.

Results

Three particle fields were Fourier transform analyzed: (1) a cali-
bration reticle or photomask, (2) a reconstructed image of a hologram of
such photomask, (3) reconstructed image of a spray hologram.

The two different softwares provided by Malvern were used where
appropriate. The first finds the best fit to a Rossin Rammler distribu-
tion, while the second is supposed to be independent of a preconceived
model. The values of $\overline{X}$ and N (defined below) were obtained with the
Rossin Rammler distribution and are indicated in the figure legends of
the model independent data.

The photomask data are summarized on Table 1. This table shows the
data obtained by analyzing the scattered light of the reconstructed
holographic image of the photomask, and also the light scattered from
the direct photomask. The parameters describing the size distribution
are $\overline{X}$ and N which are the two parameters of the Rossin Rammler distri-
bution which is given by:

$$V = e^{-(X/\overline{X})^N} , \qquad (8)$$

where V is the volume fraction of drop material occurring in drops of
diameter greater than X. The volume distribution is given by:

$$\frac{dv}{dx} = \frac{NX^{N-1}}{\overline{X}^N} e^{-(X/\overline{X})^N} \qquad (9)$$

TABLE 1

PHOTOMASK DATA

Particle Field	Particle Hologram No.	Background Hologram No.	t_A	η_D	I_o(mw)	$\bar{X}$	N	Comments
Hologram of Photomask	12	13		2%	.094/.105	48.2	3.5	Aligned receiver to background only
	12	13		2%		47.4	2.6	Aligned receiver to background only
	12	13		2%		45.2	3.8	Aligned receiver to background and to particle hologram
	21	20	20%	3%	.14/.15	47.4	2.9	Data hologram slightly misplaced
	21	20	20%	3%	.14/.15	50.4	3.8	Data hologram reposi- tioned properly
	21	20	20%	3%	.14/.15	52.1	3.9	First thing in the morning without realigning receiver
	21	20	20%	3%	.14/.15	51.5	3.7	After minor alignment
	21	20	20%	3%	.14/.15	50.5	3.8	
Direct Photomask					1.25	50.6	3.4	3-15-84
					0.14	50.6	3.4	
					0.12	50.8	3.2	3-12-84

The SMD is related to $\overline{X}$ and N by the expression:

$$SMD = \frac{\overline{X}}{\Gamma(1 - \frac{1}{N})} \tag{10}$$

To illustrate the effect of $\overline{X}$ and N on the size distribution, Figure 4 shows two volume distributions corresponding to $\overline{X}$ = 50 and N = 3 and 3.5. Large values of N correspond to narrow distributions.

Light Energy Distribution

The light energy distribution of the photomask and its holographic reconstructed image were also analyzed (Figure 5). One of the difficulties encountered in processing the holographic data stemmed from the inaccuracy in repositioning the hologram. Some of the unscattered radiation would miss the central diode and illuminate the second diode. This will show as a bin in the large size band. Figure 5 illustrates this problem. Notice the large energy level measured on Bin #15 of the holographic data. In general, however, the agreement shown between the light energy distribution produced by scattering from the real photomask and the reconstructed hologram is quite good. This probably justifies the results obtained with the Rossin Rammler software. Namely, $\overline{X}$ = 51.5, N = 3.7 for the reconstructed hologram, and $\overline{X}$ = 50.6, N = 3.4 for the direct photomask. It is not, however, clear why the N value of the hologram is larger (3.7) than the corresponding photomask

(3.4). A large value of N is associated with a narrow distribution and
it is not clear that this should be the case, given that the hologram
has additional noise which should broaden the distribution. This might
be the result of an artifact of the inversion scheme software.

Spray Hologram Data

A hologram of a spray field of synthetic fuel (SRCII) previously
acquired with a pulsed ruby laser was then analyzed. This hologram was
obtained using (almost) uniform object and reference beams and a premag-
nification of 3. To best simulate the conditions normally used by the
Malvern, a Gaussian beam of 6 mm diameter $(1/e^2)$ was used for recon-
struction. The reconstructed image had a total power of about 0.25 mw
and a (almost) Gaussian intensity profile. The divergence of the illum-
inating reconstruction wave was controlled to produce a well collimated
reconstructed wave.

Three regions of the hologram were reconstructed and analyzed with
the receiver, and a region without spray was used to obtain the back-
ground information. These data are shown on Figure 6. It is important
to realize that since the hologram was acquired with a 3:1 magnifica-
tion, the actual droplet size is 1/3 of that shown.

Figure 6 shows photograph of a given plane of the 3-D hologram, and
inserts corresponding to the locations where data were acquired. Notice
that the mean value changed from 285 μm (actual size 95 μm) at the edge
of the spray to 165 μm (actual size 55 μm) at the center. This is the
typical trend of sprays formed by simple pressure nozzles in which more
large droplets are found at the edge of the spray.

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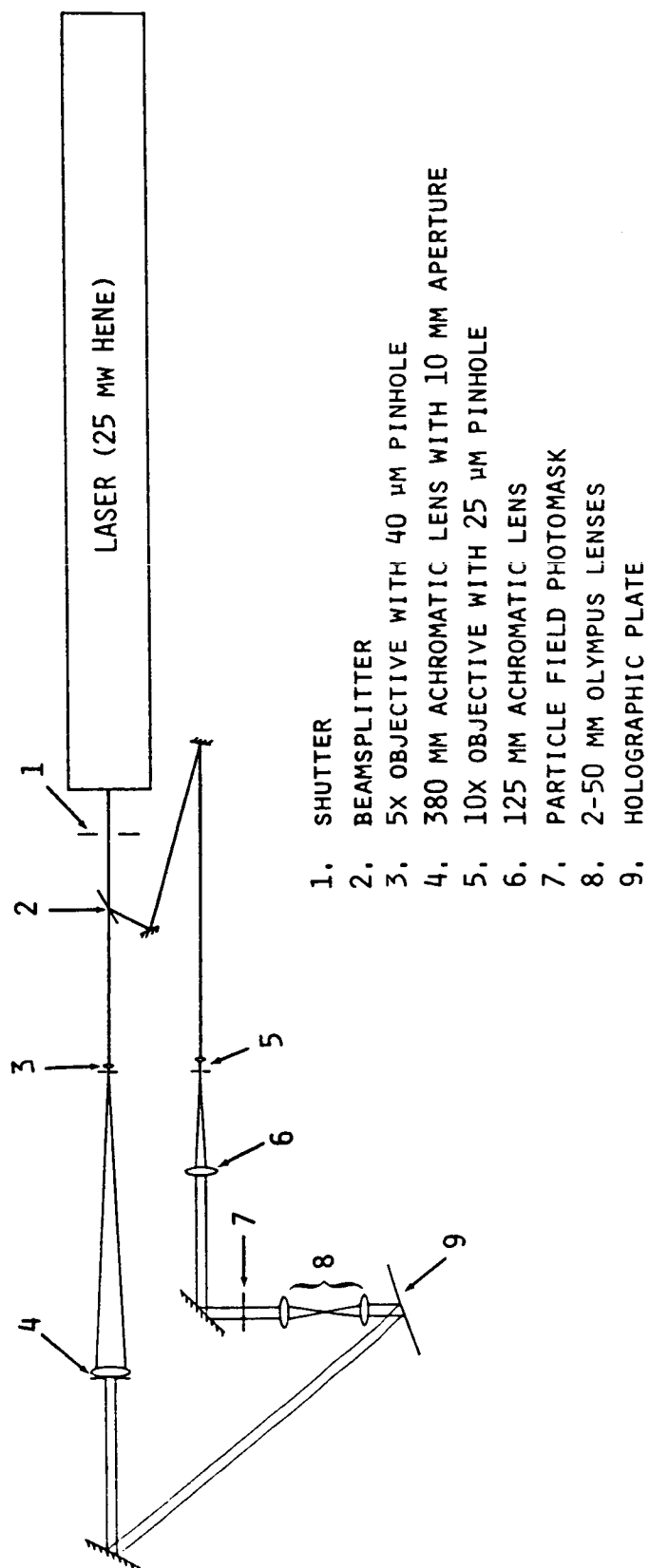## Acknowledgments

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LASER (25 MW HENE)

1. SHUTTER
2. BEAMSPLITTER
3. 5X OBJECTIVE WITH 40 μM PINHOLE
4. 380 MM ACHROMATIC LENS WITH 10 MM APERTURE
5. 10X OBJECTIVE WITH 25 μM PINHOLE
6. 125 MM ACHROMATIC LENS
7. PARTICLE FIELD PHOTOMASK
8. 2-50 MM OLYMPUS LENSES
9. HOLOGRAPHIC PLATE

SCALE: .13" = 1"

Figure 1. Schematic representation of the holographic system.
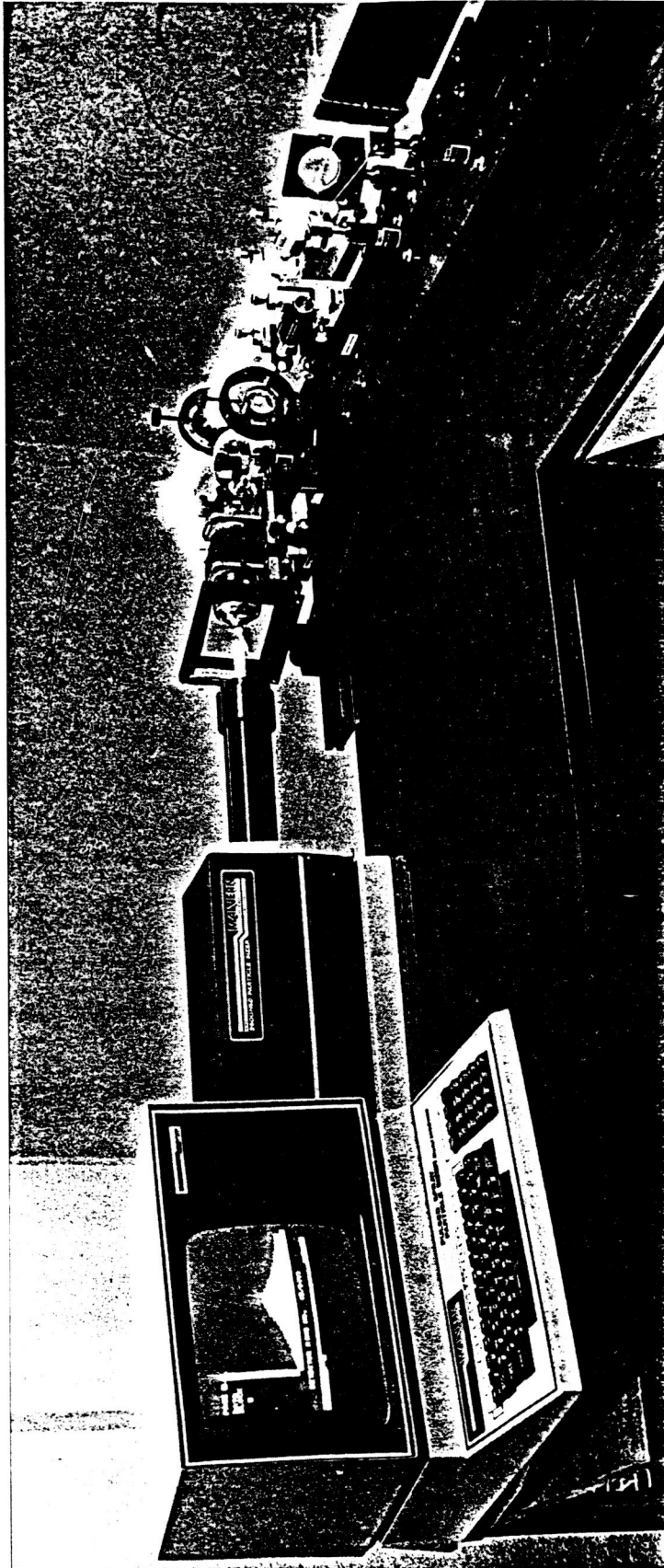
Figure 2.   Photograph of holographic system interfaced to the Malvern receiver.
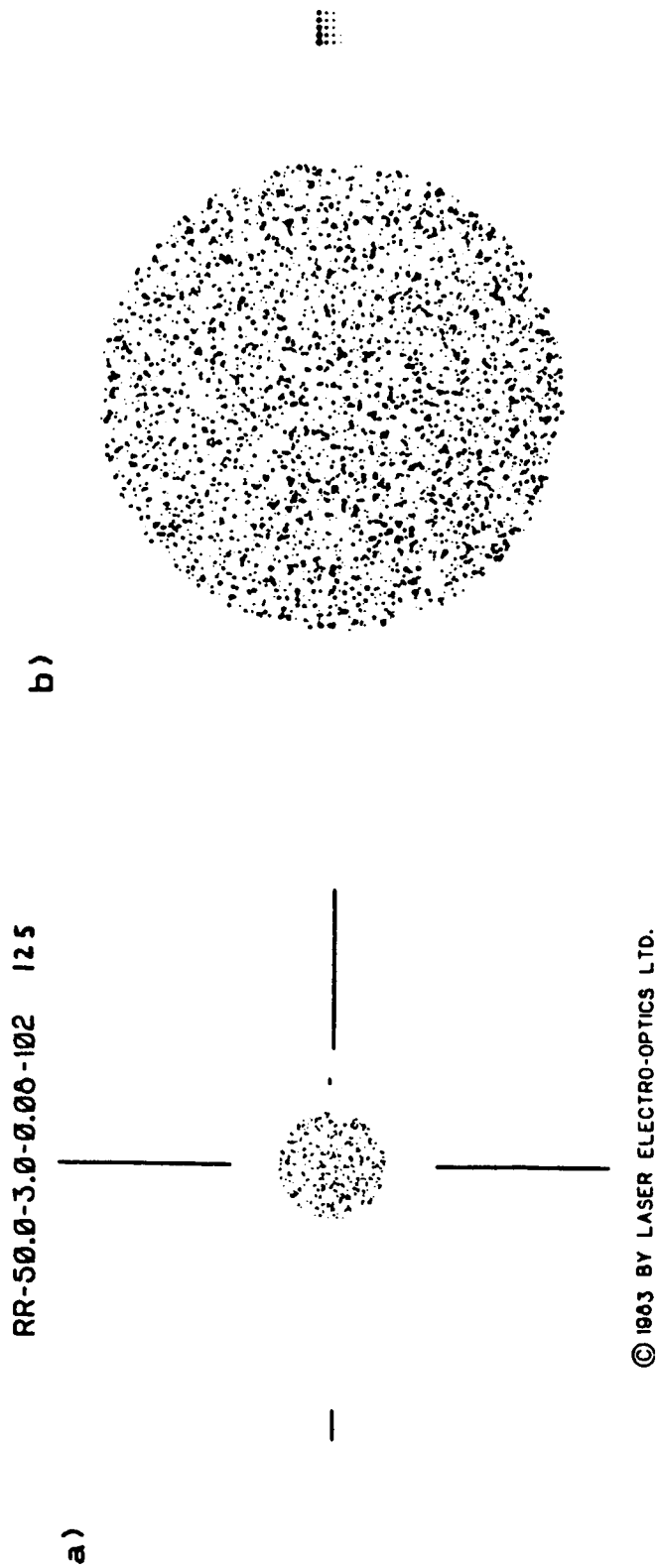
Figure 3. Photograph of calibration reticle RR-50-3.0-0.08-102-CF.
(a) Magnified 1.5X.
(b) Sample area and quality control array magnified 6.37X.
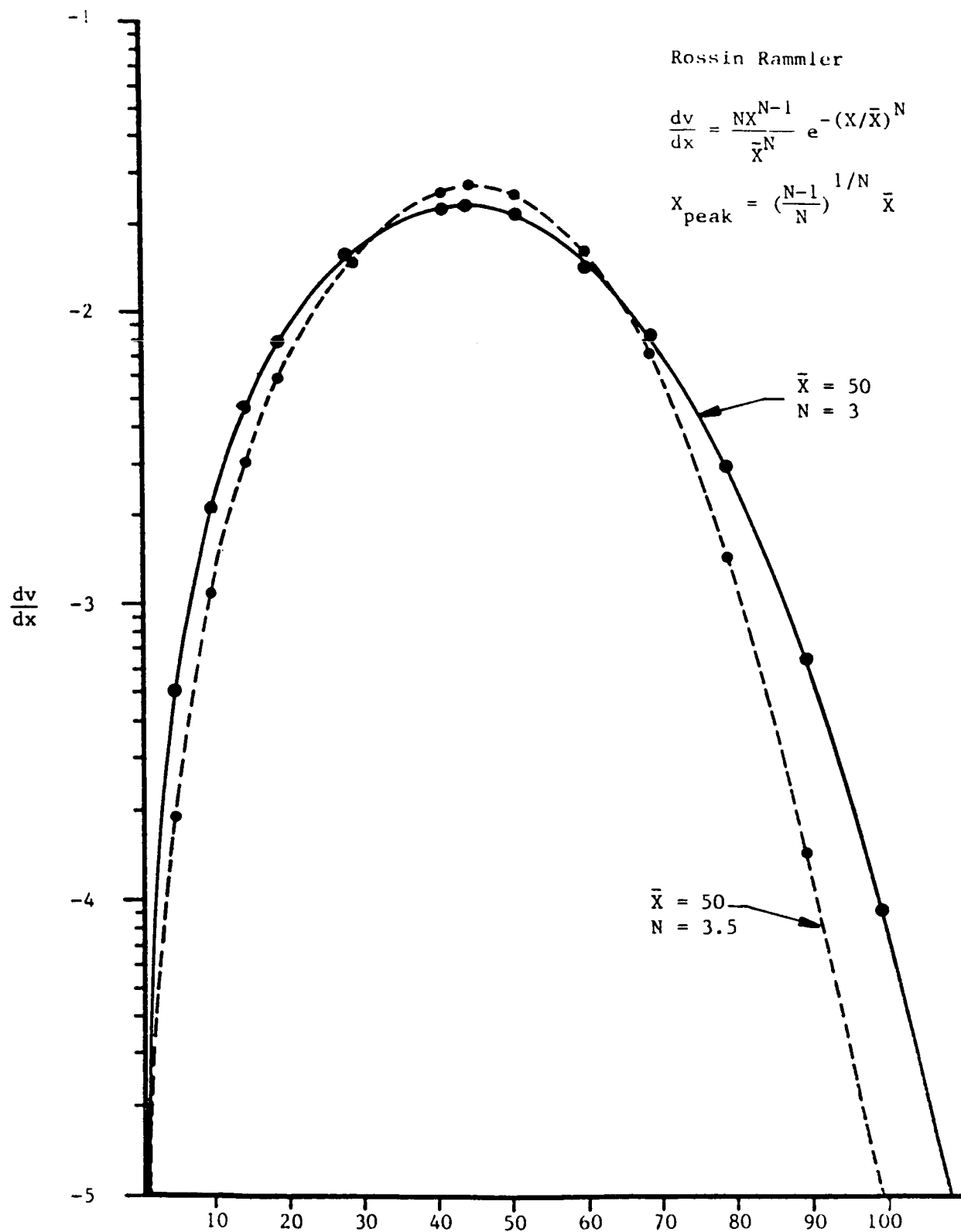
Figure 4. Effect of N on Rossin Rammler volume distribution.
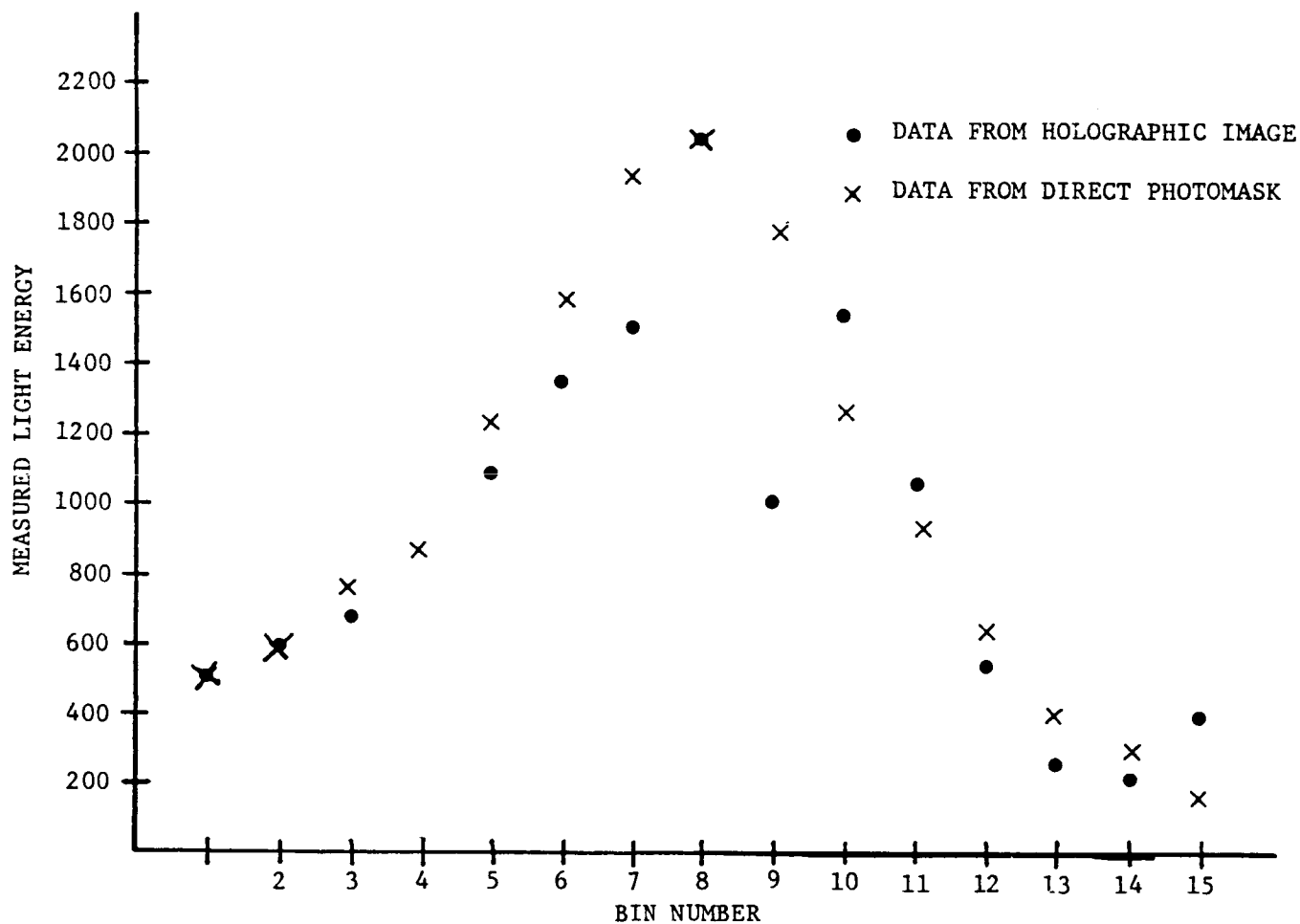
Figure 5. Measured energy levels of the lights scattered by photomask and hologram of photomask on 15 diodes of Malvern receiver. The corresponding Rossin Rammler parameters are $\overline{X}$ = 50.6, N = 3.4 (direct photomask), and $\overline{X}$ = 51.5, N = 3.7 (reconstructed hologram of photomask).

FOURIER DIFFRACTION ANALYSIS
OF A FUEL SPRAY HOLOGRAM

FUEL : SRC 2
NOZZLE : SIMPLEX
CONDITIONS : 100 PSI,75°F
PRE-MAGNIFICATION OF SPRAY HOLOGRAM : 3X
X̄,N : PARAMETERS OF ROSSIN RAMMLER DISTRIBUTION
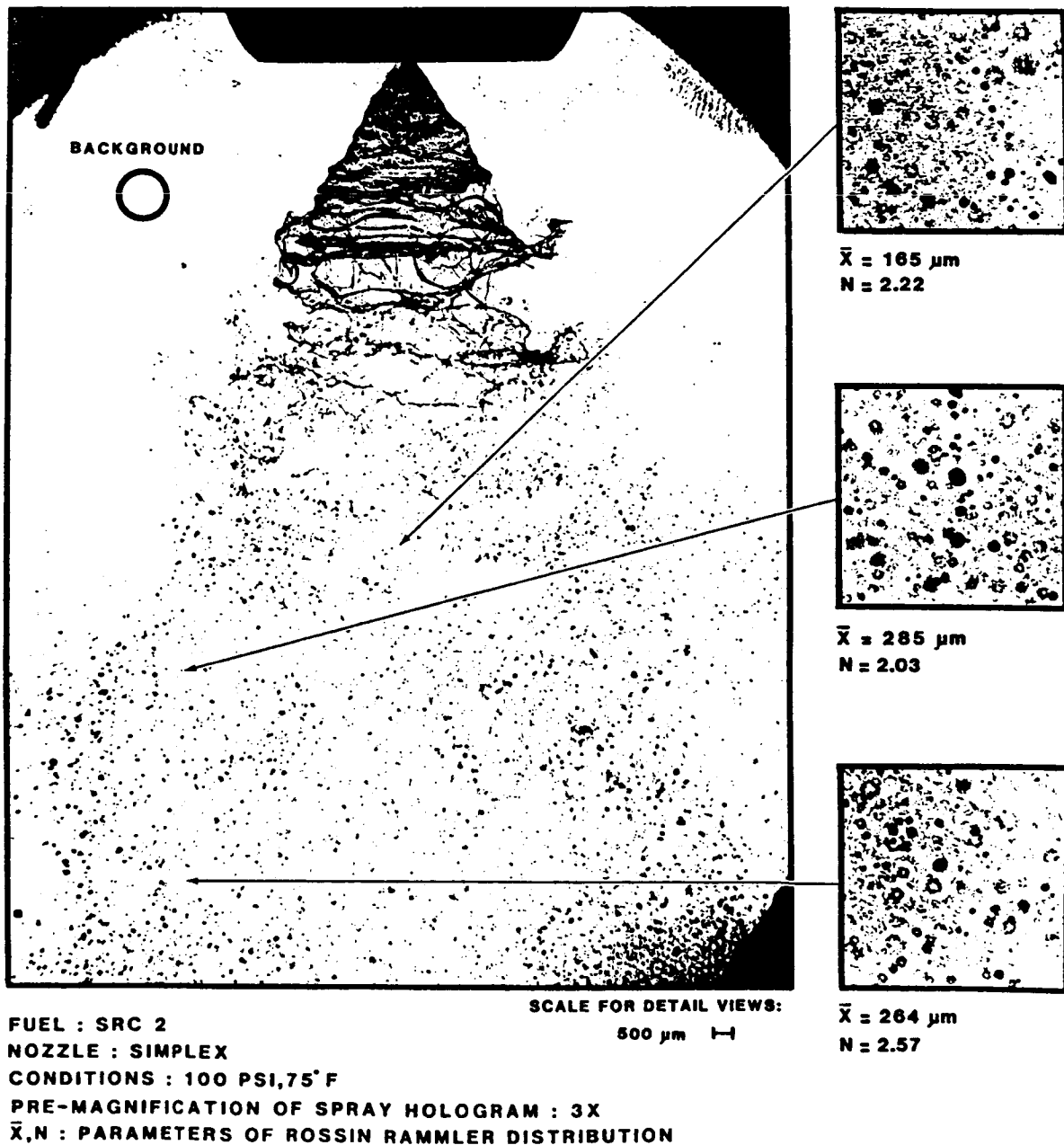
Figure 6.   Fourier transform reduction of a spray hologram
obtained with a pulsed ruby laser.

KEY WORDS

1. Particle field holography

2. Automated data reduction

LIST OF FIGURES