# A Readout Technique for the Laser Fog Disdrometer[1,2]

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## ABSTRACT

Recently a new instrument termed the laser fog disdrometer was introduced by Silverman, Thompson and Ward. As implied by the name, the function of the instrument is the determination of the size distribution of fog droplets. In design, operation and analysis this instrument represents a significant departure from the customary approaches to the problem. The basic principle of the instrument may be summarized as follows: by suitably storing the diffraction pattern associated with a droplet, both the precise size and location of the droplet may be determined. This principle can be utilized to obtain size distributions without disturbing the statistics of the sample, i.e., finite volumes may be sampled without dilution.

Originally, the data were read directly from the diffraction pattern. This type of readout is subject to two fundamental difficulties: 1) the geometry of droplets is difficult to ascertain except for simple structures; 2) if several droplets are relatively near each other in the sample volume, the resultant diffraction pattern is difficult to interpret. This first consideration does not represent a severe limitation for this application; however, it would be a serious limitation in other applications where non-spherical droplets exist. Both of these restrictions, however, are removed by the present readout technique. Physically, the new readout is based on the realization that the diffraction patterns stored by the instrument are, in fact, a new kind of hologram. Hence, the stored diffraction pattern can be used to create a real three-dimensional image of the sample volume. Since the image is fixed in time, the volume may be explored at will and the size and shape of each particle as well as its position relative to the other particles in the sample may be determined. In the present paper the concept and design of the disdrometer is reviewed and the new readout technique is discussed from both a theoretical and experimental point of view. Typical experimental results are also illustrated.

## 1. Introduction

The problem of the measurement of particle sizes and their distribution has, of course, received considerable attention in the past. The new technique introduced by Silverman *et al.* (1964) attempted to overcome some of the difficulties inherent in many other methods. This instrument was specifically designed for fog measurements on the ground and hence was called "a laser fog disdrometer." The inherent reliability of the direct method of particle size determination and relatively undisturbed sampling are features of this method.

The basic principle of this method consists of illuminating a sample volume of particles with a coherent beam of quasi-monochromatic light. Diffraction patterns are photographically recorded in a plane in the far field of the individual particles but in the near field of the whole sample volume. A distinctive Fraunhofer diffraction pattern with a coherent background is associated with each individual particle and occurs at the location of the particle as projected onto a plane perpendicular to the optical axis of the system. In the original description of the method, the readout was made directly on this photographic record by measuring characteristic features in the diffraction pattern. Experience with this type of instrumentation during the last year has led to a realization that the photographic record could be used to create a real three-dimensional image of the sample volume. Since the image is fixed in time, the volume may be explored at will and the size and shape of each particle as well as its position relative to other particles in the sample may be determined. In fact, the photographic record is a hologram (Gabor, 1949) but a hologram that is basically different from those discussed by other workers.

The method now becomes a two step process. The first step, the data collection, consists of forming the hologram (in this case a Fraunhofer diffraction pattern with coherent background) using a pulsed ruby laser as a light source to "freeze" the motion of the particles in the sample volume. The second step is a reconstruction process in which the film record of step one is illuminated with a coherent beam of quasi-monochromatic light. A three-dimensional reconstruction of the original sample volume is thus formed which can be inspected in detail to determine size, shape and distribution of the particles throughout the sample volume. The process is essentially a two step microscope that

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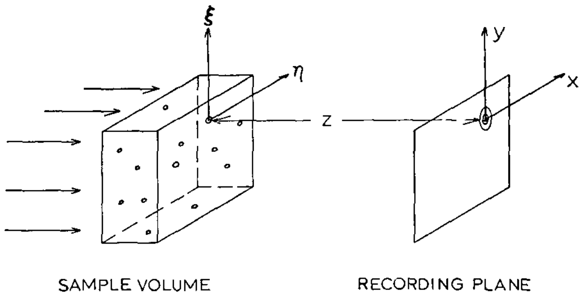

FIG. 1. The basic principle of the disdrometer. Partially coherent, quasi-monochromatic radiation illuminates the sample volume of particles. The hologram of a particular particle is recorded on film placed in the $x$, $y$ plane a distance $z$ from the particle.

can record moving particles occupying a sample depth of several centimeters. It must be stressed that the first step is not an imaging process since the final image can be obtained without the use of any lenses in the system if desired. Furthermore, magnification can be obtained by suitable choice of radius of curvature of the illuminating beam in both the steps in the process.

The first step in the process has already been adequately described in the literature and hence will only be reviewed here. The main portion of the paper will be concerned with the readout or reconstruction process. Examples will be given and some specimen results discussed. In particular, preliminary measurements made at Otis Air Force Base on fog during the summers of 1964 and 1965, as part of Project Cat Feet, are shown.

## 2. Basic principle of disdrometer

Fig. 1 illustrates the basic principle of the disdrometer. Here the method is shown using a collimated beam of quasi-monochromatic light. It must be realized that this could equally well be a converging or a diverging beam. The basic condition that is imposed upon the position of the recording plane is that

$$|z|>\frac{(\xi^2+\eta^2)_{\max}}{\lambda}. \qquad (1)$$

The patterns formed under this condition have been discussed fully in the literature (Thompson, 1963a, b, 1965; Parrent and Thompson, 1964; Silverman *et al.*, 1964). Hence only the resultant intensity distribution will be quoted here which, for a particle that presents a cross-sectional geometry $D(\xi,\eta)$ to the collimated beam, is given by

$$I(x,y,z)=1-\frac{k}{2z}\sin\left\{\frac{k(x^2+y^2)}{2z}\right\}\tilde{D}(x,y)+\frac{k^2}{4\pi^2z^2}\{\tilde{D}(x,y)\}^2, \qquad (2)$$

where $\xi$, $\eta$ are coordinates in the diffracting plane, $x$, $y$ coordinates in the observation plane, $\tilde{D}(x,y)$ is the Fourier transform of $D(\xi,\eta)$, $k=2\pi/\lambda$ and $z$ is the distance from the plane containing the particle to the recording plane. Eq. (2) contains three terms; the first is a constant intensity about which the diffraction pattern is formed, the second a cross term representing interference between the Fourier transform of the object cross section and the coherent background, and the third the square of the Fourier transform of the object cross section and is the intensity distribution in the Fraunhofer diffraction pattern of an aperture having the same cross-sectional dimensions as the particle. The second term is the dominant one—it will be noted that the sine function is independent of the particle size and only depends upon $z$; furthermore, the sine function, which for a fixed $z$ depends on $x^2+y^2$, varies more rapidly than $\tilde{D}(x,y)$.

For particles with a circular cross section of diameter $2a$,

$$\tilde{D}(x,y)=\frac{2J_1\left(\frac{kar}{z}\right)}{\left(\frac{kar}{z}\right)}, \qquad (3)$$

where $r=(x^2+y^2)^{\frac{1}{2}}$ and $J_1$ is the usual notation for a Bessel function of the first kind. Hence, Eq. (2) becomes

$$I(r,z)=1-\frac{ka^2}{2z}\sin\frac{kr^2}{2z}\left[\frac{2J_1\left(\frac{kar}{z}\right)}{\left(\frac{kar}{z}\right)}\right]+\frac{k^2a^4}{4z^2}\left[\frac{2J_1\left(\frac{kar}{z}\right)}{\left(\frac{kar}{z}\right)}\right]^2. \qquad (4)$$

In the earlier paper (Silverman *et al.*, 1964), the particle size was determined from this type of record. Fig. 2 is a typical hologram of fog particles in the 5 to 40 $\mu$ size range. These droplets were recorded at Otis Air Force Base on 19 July 1965 at 0505 EST. Some of the very large diffraction patterns are caused by dirt in the optical system. The holograms of dirt particles reconstruct outside of the fog sample volume and can not be confused with actual fog particles. Two difficulties arise when data is reduced by direct study of the hologram itself. First, except for very simple objects, it is not practical to determine the geometric shape of the particle which formed the hologram. Second in areas where the diffraction patterns of several particles over-

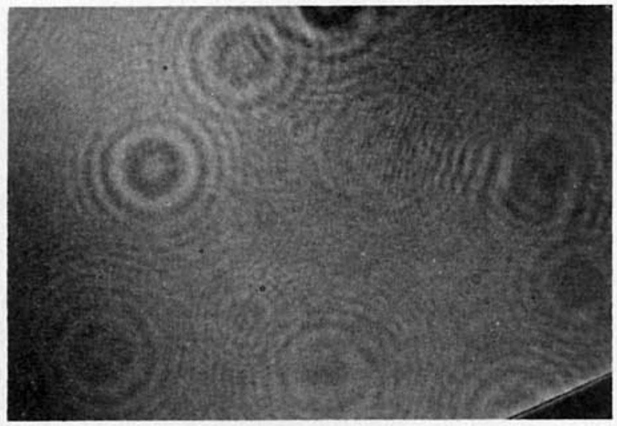

Fig. 2. A typical hologram of fog particles. This data was recorded at Otis Air Force Base on 19 July 1965 at 0505 EST. Particles are in the size range 5–40 $\mu$ diameter. A sample volume of 0.2 cm$^2$ cross section is shown. The total sample cross section of the instrument was 1 cm$^2$.

lap it is impossible to accurately size any one of the individual particles.

### 3. Principle of readout

The readout method consists of illuminating the film records obtained in step one with a coherent beam of quasi-monochromatic light as shown in Fig. 3. For the purpose of this discussion a collimated beam will again be assumed but, of course, this beam could also either be converging or diverging. For a collimated beam of quasi-monochromatic light of the same wavelength as that used in forming the original diffraction pattern, a reconstruction of the original particle is formed at the same distance from the film as the original was from the recording plane. Under these circumstances, the reconstruction is of unit magnification. If a different wavelength of light is used for the reconstruction, then under the above conditions of collimated light for both the formation and the reconstruction, the magnification is still unity but the plane in which the reconstruction takes place is changed. This type of photographic record which contains all the necessary information to form an image when suitably illuminated is called a hologram. A considerable amount of literature exists discussing holograms of the type that are basically Fresnel diffraction patterns with coherent background (Gabor, 1949; Leith and Upatnieks, 1963, 1964). However, the consideration of Fraunhofer (far field) diffraction patterns with coherent background is quite new and to distinguish them from the Fresnel type, the word Fraunhofer (far field) hologram was introduced (Thompson, 1965).

The mathematical details of the reconstruction process have been discussed elsewhere (DeVelis *et al.*, 1966) and hence only a summary of the results pertinent to this paper will be given here.

The amplitude transmission $t(x,y,z)$ of the hologram,

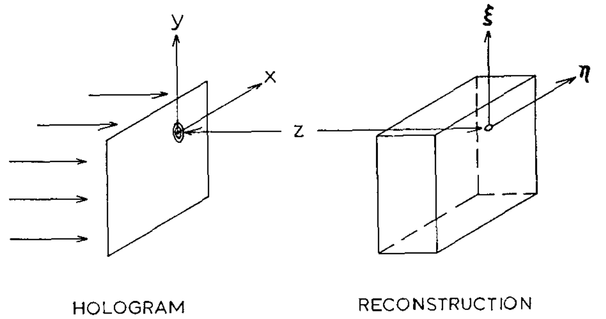

Fig. 3. The basic principle of the readout. The hologram located in the $x,y$ plane is illuminated by partially coherent quasi-monochromatic light. The hologram of a particular particle reconstructs a real image of the particle at a distance $z$. The distance $z$, size and shape of the real image and its location in the $\xi$, $\eta$ plane are uniquely determined by the hologram.

when illuminated coherently, is

$$t(x,y,z)=1+\gamma\frac{k}{2\pi z}\sin\frac{k(x^2+y^2)}{2z}\tilde{D}(x,y), \qquad (5)$$

where $\gamma$ is the slope of the $H$ and $D$ curve of the film. The final term containing the factor $[\tilde{D}(x,y)]^2$ has been

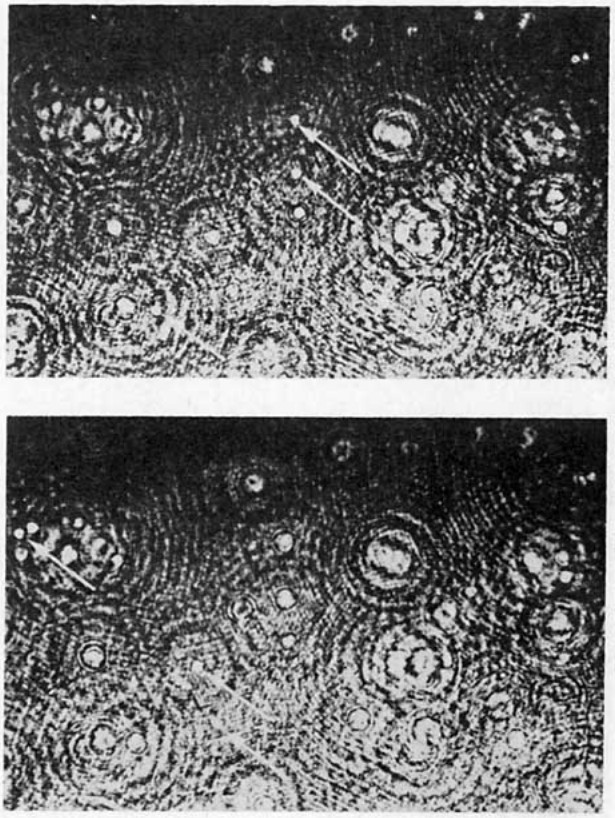

Fig. 4. Successive planes of the real image reconstructed from a hologram taken of a volume of suspended 30 $\mu$ lycopodium particles. These planes are separated by 5 mm along the optical axis in the volume of suspended particles. The area of the print represents a 1.7 mm$^2$ sampling cross section. The total sample volume recorded by the hologram was 1 cm in depth and 1 cm$^2$ in cross section. The particle density is approximately $2\times10^3$ cm$^{-3}$.

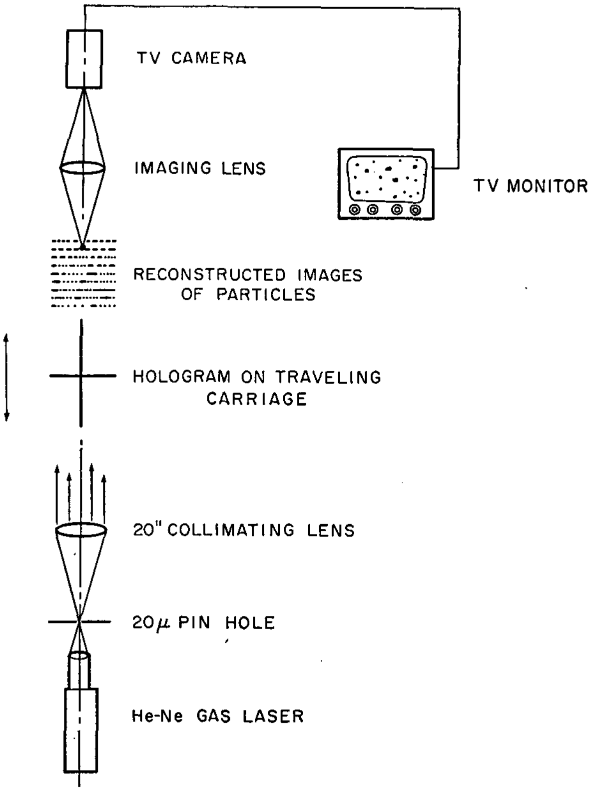

FIG. 5. Schematic of the present readout instrument.

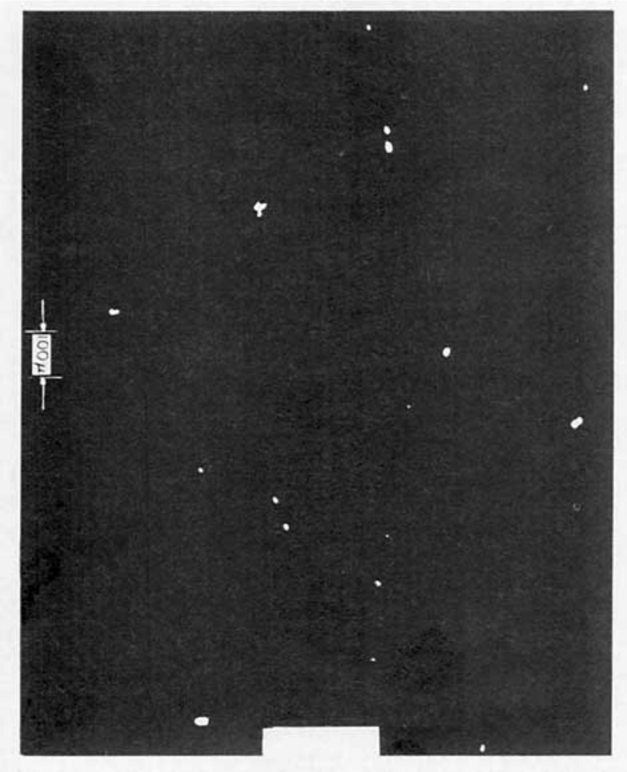

FIG. 6. Reconstructed 5–50 $\mu$ particles photographed from the television monitor in the readout instrument. The contrast control in the closed circuit television system was used to discriminate against low level background noise in the reconstructed image.

ignored as being small compared to the other terms. The intensity distribution in the reconstructed image is then given by

$$I(\xi,\eta)=1+\frac{\gamma}{2}D(\xi,\eta)+\frac{\gamma^2}{4}[D(\xi,\eta)]^2. \qquad (6)$$

Here only the reconstruction of a single particle has been given; however, if the film record was a hologram of a sample volume of particles, then each particle would be reconstructed in its correct relative position. It is equally important that the cross-sectional geometry of each particle is also reconstructed. Fig. 4 shows the effect of a volume reconstruction of particles. A hologram was made of a suspension of 30 $\mu$ lycopodium particles. The prints in Fig. 4 were taken in two planes separated by 5 mm in the sample volume. Both prints include the same cross section of the reconstruction image, but different particles are seen to be in focus in each plane.

## 4. The readout instrument

The present readout system (Fig. 5) uses a helium-neon gas laser to provide the coherent quasi-monochromatic collimated illumination necessary for image reconstruction. The hologram is located on a motor driven traveling carriage which allows continuously spaced successive planes of the reconstructed sample volume to be imaged onto the photo-sensitive surface of a closed circuit TV camera. The traveling carriage can scan a reconstructed sample volume of up to 125

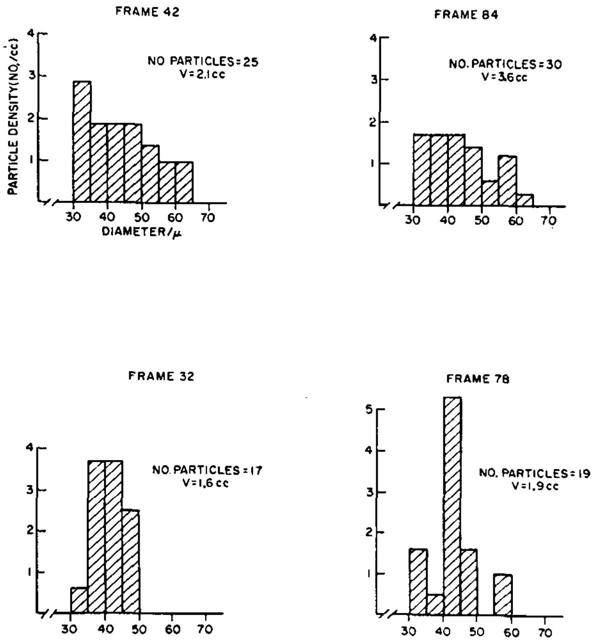

FIG. 7. Histograms of selected individual frames of fog data taken at Otis Air Force Base on 17 August 1964 between 2350 and 2400 EST. A total of 110 frames were taken in this period.

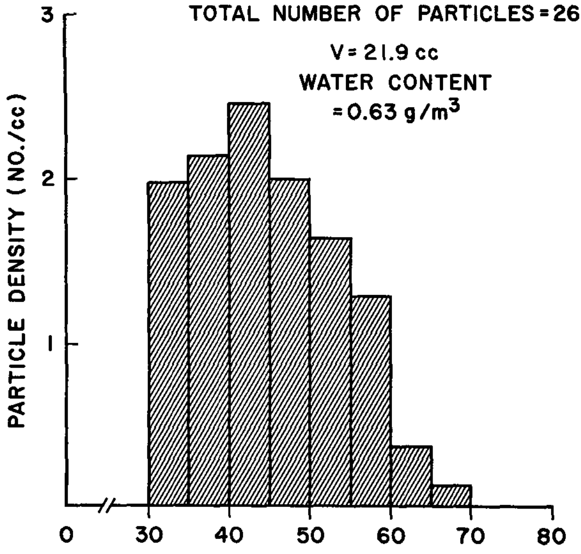

Fig. 8. A composite histogram made from 8 frames of fog data of Fig. 7.

cm in depth at a uniform rate. The present laser fog disdrometers magnify the sample volume 5× before the hologram is formed. Since distances along the optical axis are increased as the magnification squared in the reconstruction process, a scanning distance of 125 cm allows an actual sample volume 5 cm deep to be imaged by the readout instrument. The present laser fog disdrometers record a volume 7 cm in depth. These data are currently being read in two overlapping steps (see Section 5).

The use of a closed circuit TV system to display the images of fog particles has several distinct advantages. Image magnification and increased image brightness are obtained simultaneously. The television contrast may be adjusted such that only the in-focus particle images are displayed on the monitor screen. This is possible since the out-of-focus particles, or holograms, have less intensity than the focused images, and the contrast control can be used to discriminate between in-focus and unfocused images thereby clipping out unwanted signal in the visual display. Fig. 6 is a photograph taken of the television monitor screen showing reconstructed 5–50 $\mu$ particles. Unwanted background noise has been discriminated against by using the contrast control of the closed circuit TV system and the non-linear properties of the photographic film. The original target used in construction of the hologram was a microscope slide sprinkled with particles.

This discrimination or clipping can be used to further advantage to reduce a volume image to one photograph containing only focused particles. The traveling carriage carrying the hologram is moved at a uniform rate through the sample depth focusing successive planes onto the television monitor. Only in-focus particles are displayed as the volume is scanned. These images are photographically recorded by taking a time exposure of the television monitor during the volume scan.

## 5. Preliminary data and results

Fig. 7 shows histograms of selected frames of fog data taken on 17 August 1964 between 2350 and 2400 EST at Otis Air Force Base. The sample volume of each frame and the total number of particles counted is given with each histogram. Fig. 8 is a composite histogram plotted from 8 data frames taken within the same time period. The variations between histograms of different frames indicates that one frame alone was not a meaningful statistical sample of the fog. The resolution limit of the system was approximately 30 $\mu$ when this data was recorded.

Fig. 9 shows the present laser fog disdrometer at the Otis Air Force Base field site. The fog volume is sampled between the two dish-like plates and is 7 cm deep with a cross sectional area of 1 cm$^2$. The particle holograms are recorded on the film at 5× magnification. Two instruments were operated in the field, one with a maximum sampling rate of 1 frame sec$^{-1}$, the other with a sampling rate of one frame every 40 sec. Kodak 70 mm High Definition Aerial Film SO-243 was used to

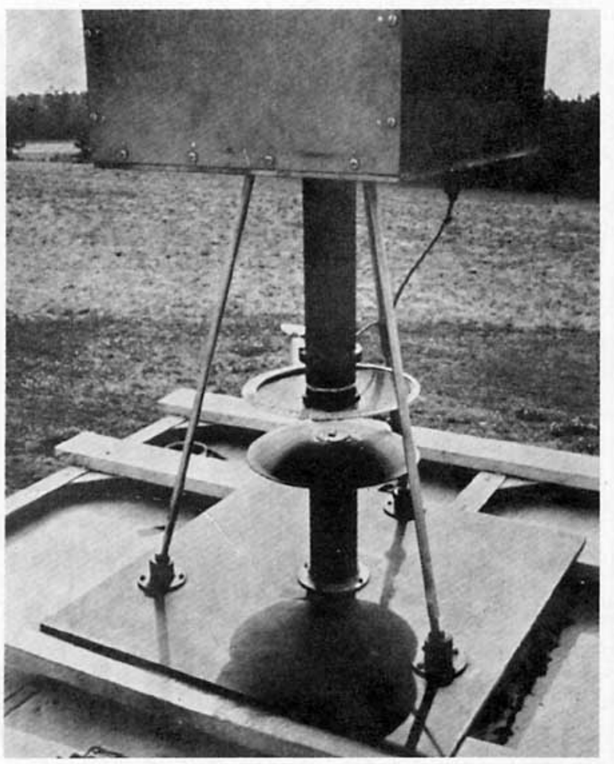

Fig. 9. Photograph of the laser fog disdrometer at the Air Force Cambridge Research Laboratory fog study site at Otis Air Force Base. The sample volume is in the area between the dish like curved plates. The sample volume is 1 cm$^2$ in cross section by 7 cm deep. The pulse ruby laser light source is inside of the cabin below the deck. The top box houses the film transport and time imaging set up. The imaging lens is in the top vertical tube just above the sample volume.

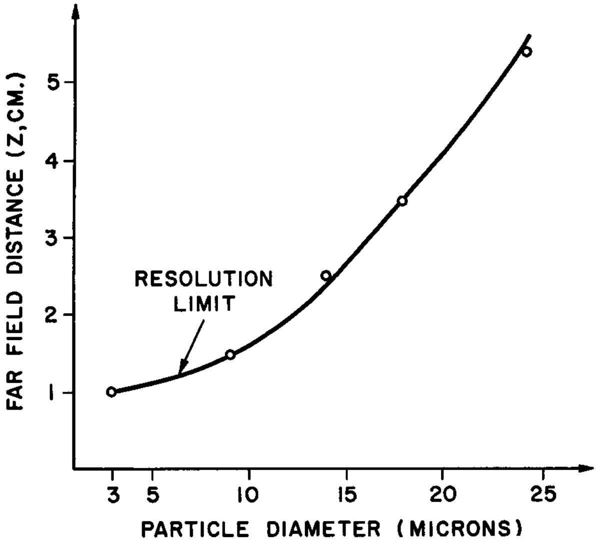

FIG. 10. Experimental verification of particle size resolution vs. far field recording distance. All particles falling below the curve are properly recorded.

record the holograms. It was not possible to use higher resolution photographic plates because of the sampling rate required. A magnification of 64X is used in the readout device. This gives the system a total magnification of 320X.

The hologram technique for recording small particles is essentially a two-step imaging system and hence the system resolution for partially coherent radiation has been calculated (Parrent and Reynolds, 1964) using methods applicable to imaging systems. The design goal of the present instruments of recording 4–200 $\mu$ particles has been met. However, as a further check resolution was measured in the laboratory using particles of known size. This result is given in Fig. 10.

Data taken on 19 July 1965 is given as a histogram in Fig. 11. Data reduction is being carried out by the Cloud Physics Branch of the Air Force Cambridge Research Laboratories as part of the fog study, Project Cat Feet. Currently, further research is being conducted to automate the readout step in the hologram method of recording small particles.

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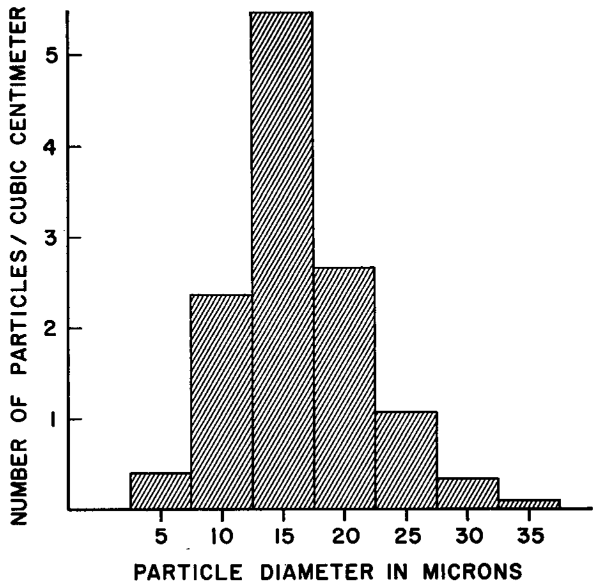

FIG. 11. Preliminary histogram of fog data recorded on 19 July 1965 at 0505 EST at Otis Air Force Base. Sampling rate was 6 frames min$^{-1}$. A total of 143 particles were measured to the nearest 5 $\mu$ in diameter from 4 successive frames of data. These initial results are from the data reduction being done by the AFCRL Cloud Physics Branch as part of Project Cat Feet.

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