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POSSIBLE USE OF TWO LASER BEAMS TO DETERMINE PARTICLE-SIZE DIST--ETC(U)
JAN 79 D E WORTMAN
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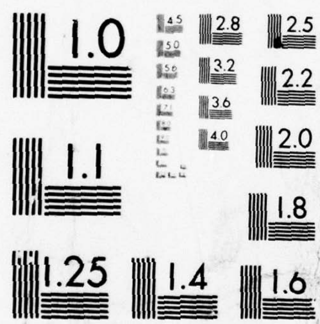

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A study was made to determine whether particle-size distributions for small diameter aerosols (radius $\leq$20 µm) such as fog can be determined by a new technique based on resonantly distorting the liquid drops by an oscillating electric field at the drops' mechanical vibrational frequencies. This field was transmitted by a linearly polarized CO_2 laser of intensity 100 W/cm^2 amplitude modulated at frequencies between 4×10^4 and 3×10^6 Hz, which

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20. ABSTRACT (Cont'd)

micrometers

correspond to the fundamental vibration frequencies of drops varying in radius from 21.2 to 1.19 μm. An unmodulated, 2-mW He-Ne laser was beamed along the path of the CO_2 radiation, and scattering of this light was observed. The intensity of the He-Ne light scattered from the drops at the resonance frequency should be proportional to the density of the drops in the fog that oscillate at that frequency. A sensitive detection system able to measure ac signals with intensities as low as 10^{-17} W collected the scattered He-Ne light. No amplitude-modulated component was detected in the scattered ~~He-Ne~~ light over the modulation frequency range. Calculations were also made showing that the amplitude of oscillation for 20-μm radius drops illuminated with 100 W/cm^2, for example, is 3×10^{-10} m, and the oscillation amplitudes, which scale directly with the intensity of the CO_2 laser, decrease for smaller drops as the 5/2 power of the radius. Estimates of the oscillation amplitudes required to produce measureable amplitude-modulated signals in the scattered light were obtained from intensity calculations. Preliminary results of the intensity calculations suggest that this technique may be practicable for determining particle-size distributions for drops of radii ≥ 20μm and that oscillations amplitudes should be easily detected for liquid drops corresponding to 0.5-percent changes in the radii of such drops. In addition, the calculated results for millimeter-size water drops indicate that the drops driven resonantly may be distorted to the same b/a ratio, the ratio of the maximum-to-minimum axis for a prolate spheroid, in electric fields lower in amplitude than Billings and Holland found experimentally.

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1. INTRODUCTION

The primary purpose of this study was to determine whether particle-size distributions for small-diameter aerosols (radius ≤ 20 µm) such as fog can be determined by a new, novel technique that uses a method of resonantly distorting the liquid drops by an oscillating electric field.* This technique makes use of the fact that a liquid drop elongates along the axis parallel to an applied electric field.[1,2] It can be shown that the elongation is independent of the sign of the field; hence, the force acting on the drop is proportional to the square of the electric field. The phenomenon suggests the following two cases, where a drop can be resonantly driven[3] at its natural vibrational frequency by an alternating electric field.

For case 1, suppose that a polarized beam of electromagnetic radiation is modulated so that the amplitude of the electric field varies as $E = E_o \cos \omega t\ (1 + m \cos \omega_m t)$, where E_o is a constant, $\omega/2\pi$ is the carrier frequency, $\omega_m/2\pi$ is the modulation frequency, and m is the index of modulation. The force on the drop, which is proportional to E^2, varies approximately as $E_o^2/2\ (1 + 2\ m \cos \omega_m t)\ (1 + \cos 2\omega t)$ for $m \ll 1$. If ω is so large that the drop cannot mechanically respond to 2ω, then the force on the drop varies as $E_o^2(1 + 2\ m \cos \omega_m t)/2$. The modulation frequency, ω_m, can be adjusted to match the mechanical vibrational frequency,[4] ω_n, given by

$$\omega_n = \sqrt{\frac{n(n-1)(n+2)\tau}{\rho a^3}} , \tag{1}$$

where n is the mode number, τ is the surface tension, ρ is the density, and a is the drop radius. As other workers have pointed out,[5] the lowest order (n = 2) mode dominates; thus, resonance occurs when the electromagnetic wave incident on the liquid drop is amplitude modulated at $\omega_2 = (8\tau/\rho a^3)^{\frac{1}{2}} = \omega_m$.

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[1] *W. A. Mack, Proc. Roy. Soc. London A* <u>*133*</u> *(1933), 565.*

[2] *Sir G. Taylor, Proc. Roy. Soc. London A* <u>*280*</u> *(1964), 383.*

[3] *C. T. O'Konski and H. C. Thacher, J. Phys. Chem.* <u>*56*</u> *(1953), 955.*

[4] *Lord Rayleigh (J. W. Strutt), The Theory of Sound (Dover, New York 1877, revised 1894, reprinted 1945).*

[5] *P. R. Brazier-Smith, M. Brook, J. Latham, C. P. R. Saunders, and M. H. Smith, Proc. Roy. Soc. A* <u>*322*</u> *(1971), 523.*

**The research which developed the new technique was conducted at the Harry Diamond Laboratories by R. P. Leavitt, C. A. Morrison, N. Karayianis, and D. E. Wortman. This research has not been formally reported.*

For case 2, suppose that an alternating voltage is applied to two condenser plates which produce an electric field varying as $E = E_o \cos \omega_m t$. The force on a liquid drop situated between these plates varies as $E_o^2(1 + \cos 2\omega_m t/2)$. A resonance occurs for this case when $\omega_2 = 2\omega_m$.* Hence, the electric field driving the drops will be only $\frac{1}{2}\omega_2$, whereas $\omega_2 = \omega_m$ for case 1. Billings and Holland[6] have previously measured millimeter-size water drops under experimental conditions that correspond to this latter case.

In another earlier work, Brook and Latham[7] demonstrated that single vibrating millimeter-size drops can produce modulation of backscattered microwave signals and the modulation frequency can be related to drop size. Also, some earlier studies[1-6,†] have shown that millimeter-size water drops can be caused to elongate in dc electric fields, to vibrate in ac electric fields, and to elongate so much that they rupture in electric fields of the order 10^4 V/cm. (R. P. Leavitt, C. A. Morrison, and D. E. Wortman, of the Harry Diamond Laboratories--HDL--have done similar studies of which data are unpublished.) In addition, Billings and Holland[6] found that rupture for drops smaller than 3 mm occurred at considerably lower field strengths when they varied the frequencies of the applied field near the drops' resonance frequencies than occurred in the static case. Results of these earlier studies suggest that somewhat weaker amplitude-modulated electric fields, as transmitted by a CO_2 laser, might suffice to cause mechanical oscillations of detectable magnitude for drops driven at their resonance frequencies.

In this work, aerosol drops contained in a fog chamber were illuminated with a polarized, amplitude-modulated, CO_2 laser beam that acted to drive the drops, as in case 1. In order to determine whether the drops were oscillating mechanically, a second unmodulated He-Ne laser was beamed collinear with the CO_2 laser. Scattering of the He-Ne radiation by the drops was then detectedby a sensitive detection system that could measure ac signals with intensities as low as about 10^{-17} W. The intensity of the He-Ne light scattered from the drops at the

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[1]*W. A. Mack, Proc. Roy. Soc. London A* *__133__* *(1933), 565.*

[2]*Sir G. Taylor, Proc. Roy. Soc. London A* *__280__* *(1964), 383.*

[3]*C. T. O'Konski and H. C. Thacher, J. Phys. Chem.* *__56__* *(1953), 955.*

[4]*Lord Rayleigh (J. W. Strutt), The Theory of Sound (Dover, New York 1877, revised 1894, reprinted 1945).*

[5]*P. R. Brazier-Smith, M. Brook, J. Latham, C. P. R. Saunders, and M. H. Smith, Proc. Roy. Soc. A* *__322__* *(1971), 523.*

[6]*J. J. Billings and D. F. Holland, J. Geophys. Res.* *__74__* *(1969), 6884.*

[7]*M. Brook and D. J. Latham, J. Geophys. Res.* *__73__* *(1968), 7137.*

**Earlier noted work of Morrison, Karayianis, and Wortman, HDL.*

†*Further references to the earlier work are listed at the end of this report in a Selected Bibliography.*

resonance frequency, $\omega_2 = \omega_m$, should be proportional to the density of drops in the fog that oscillate at that frequency. The particle-size distribution of the fog can then be obtained* by varying the modulation frequency and examining the intensity of the ac signal[7] produced by the scattered light.

The scattered He-Ne laser signal of wavelength $\lambda = 0.6328$ µm was observed for amplitude-modulation frequencies of the CO_2 radiation from 4×10^4 to 3×10^6 Hz, which correspond to fundamental resonance frequencies of drops of radii varying from 21.2 to 1.19 µm. No amplitude modulation was detected in the scattered He-Ne radiation. Calculations were then made to determine the amplitudes of the oscillations for the drops when illuminated, as was done in this experiment, by the CO_2 radiation of intensity 100 W/cm^2. It was found that the amplitude of oscillation calculated for 20-µm drops, for example, is 2.7×10^{-10}m, which is less than the 10^{-7} m amplitude required to produce measurable signals. Also, the oscillation amplitudes are proportionately smaller for smaller drops. Intensity calculations,[8,†] allowed us to estimate that 0.5 percent changes in radii for the drops of radii between 1.19 and 21.2 µm should produce measurable amplitude-modulated signals in the scattered light. In the experiment performed only millimeter-sized drops would have distorted with such measureable magnitudes when illuminated with a 100-W/cm^2 polarized beam that had an index of modulation of about 0.4. The fundamental oscillation frequencies for millimeter-sized drops correspond to frequencies outside the range detected in this work. However, in section 4 comparisons are made of oscillation amplitudes calculated for millimeter-sized drops with the experimental results of Billings and Holland.[6] In section 4 calculated results for water drops of various radii are also given that show the amount of distortion, which scales directly with the incident intensity, produced by a radiation flux of 100-W/cm^2 intensity.

2. APPROACH AND THEORETICAL CONSIDERATIONS

In this work an oscillating electric field, which was provided by a linearly polarized, amplitude-modulated, continuous-wave (cw) CO_2 laser beam, acted on aerosol drops to drive the drops at their mechanical resonance frequencies. A second unmodulated, cw He-Ne laser beam was shown collinear with the first beam. Scattering from the drops, which were in the path of the laser beams, was detected in the visible

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[6] *J. J. Billings and D. F. Holland, J. Geophys. Res.* 74 *(1969), 6884.*
[7] *M. Brook and D. J. Latham, J. Geophys. Res.* 73 *(1968), 7137.*
[8] *P. W. Barber and D. S. Wang, Applied Optics* 17 *(1978), 797.*
**Earlier noted work of Morrison, Karayianis, and Wortman, HDL.*
†*P. W. Barber (private communication).*

wavelength region. If the cross sections of the drops change sufficiently at the mechanical oscillation frequencies of the drops, a detectable amplitude-modulated component will be observed in the scattered He-Ne light.

The amplitude of the electric field acting to distort the liquid drops is related[9] to the power in the beam by the expression

$$E = \sqrt{2Ic\mu} \qquad \text{(in mks units)}, \tag{2}$$

where I = power/meter^2 of the laser, c is the velocity of light, and μ is the permeability of free space ($\mu = 4\pi \times 10^{-7}$ H/m). This relation was obtained by time averaging the Poynting vector for a transverse wave propagating in free space. The force on a drop is proportional, in the notation of Jackson,[9] to the square of the electric field, or

$$F = KE^2 \tag{3}$$

where K is a constant which depends on the geometry, dielectric constant, etc. If a time average of this force is taken over a period of the CO_2 laser frequency, T_L, which is short compared to a period of the amplitude modulation, one obtains

$$F(t) = \frac{1}{T_L}\int_0^{T_L} F(t)\, dt = \overline{KE^2}(t) \quad . \tag{4}$$

How this force, applied by the modulated, cw laser beam, acts to distort and drive liquid drops is the subject of another paper* and only the pertinent results are given here. In that paper,* solutions were obtained for a viscous liquid drop acted on by an oscillating electric field. The approach taken was like that of Rayleigh's[4] treatment of an oscillating water drop in that the formulas were derived for small amplitude distortions from spherical shapes. As pointed out by P. R. Brazier-Smith et al[5] good agreement with Rayleigh's result has been obtained experimentally for cases where large amplitude vibrations occur.

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[4]*Lord Rayleigh (J. W. Strutt), The Theory of Sound (Dover, New York 1877, revised 1894, reprinted 1945).*

[5]*P. R. Brazier-Smith, M. Brook, J. Latham, C. P. R. Saunders, and M. H. Smith, Proc. Roy. Soc. A 322 (1971), 523.*

[9]*J. D. Jackson, Classical Electrodynamics (Wiley, New York, 1963, p. 205).*

**R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.*

In the treatment of the problem, it was assumed* that the distance from the origin to a point on the surface of the droplet can be expanded in a Legendre series as

$$R(t) = a_o(t) + \sum_{k=1}^{\infty} a_k(t)\ P_k(\cos\theta) \quad , \tag{5}$$

where the a_k's are constrained so that the volume of the drop remains constant at $(4\pi/3)a^3$ and a is the radius of the undistorted drop. The potential energy, U_S, of the drop due to surface tension, γ, is the area of the drop multiplied by the surface tension, or

$$U_s = \gamma\int_0^{2\pi} d\phi \int R \sin\theta ds \quad , \tag{6}$$

where ds is the arc length along the surface. When equation (5) was substituted into (6) and the necessary integration was performed, the potential energy due to surface tension correct through a_k^2 was found.*

The kinetic energy, T, was found* by evaluating the integral

$$T = \int \tfrac{1}{2}\rho \quad v^2 \quad d\tau \tag{7}$$

where ρ is the density and v is the velocity. A potential function ϕ was found for the case of an incompressible liquid with no sources, sinks, or rotating flows, where

$$\phi = \sum_n \beta_n\ r^n\ P_n \quad . \tag{8}$$

Leavitt et al* showed that in the absence of other energy sources, a Lagrangian can be formed, where L = T - V, to obtain equations of motion for the $a_k(t)$ in equation (5) in agreement with the results of Rayleigh.[4] The more generalized Lagrangian used by Leavitt et al* contained the electromagnetic energy and the viscosity.

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[4] *Lord Rayleigh (J. W. Strutt), The Theory of Sound (Dover, New York 1877, revised 1894, reprinted 1945).*

**R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.*

The electromagnetic wave acting to drive the liquid drop was considered* to have a wavelength large in comparison with the drop radius, and it was further assumed that there is no free charge. The potential is then a solution of Laplace's equation, $\nabla^2\phi = 0$, and $\vec{E} = -\nabla\phi$. The appropriate solutions are

$$\phi^o = \sum_n \frac{A_n}{r^{n+1}} P_n - ErP_1 \tag{9}$$

and

$$\phi^i = \sum_n B_n r^n P_n \tag{10}$$

where E is the electric field in the region in the absence of a drop and ϕ^o and ϕ^i are the electromagnetic potentials outside and inside the drop. The electromagnetic energy stored in the drop is given by the expression

$$U_E = \frac{(\varepsilon - 1)}{8\pi} \int \vec{E}^i \cdot \vec{E}\, d\tau \quad , \tag{11}$$

where ε is the dielectric constant of the drop at the laser frequency, $\vec{E}^i$ is the electric field inside the drop, and the integral covers the volume of the drop. After appropriate boundary conditions were used to evaluate the A_n and B_n of equations (9) and (10), and after the necessary integration was performed by also using equation (5) in equation (11), an expression for U_E in terms of the a_k was obtained.*

In considering the dissipation of energy due to viscosity, Leavitt et al* used the results of Lamb[10] for the case of an irrotational fluid where the rate of energy dissipation was found to be

$$F = -\frac{\mu}{2}\int \vec{\nabla}\ (v^2)\ \vec{ds} \tag{12}$$

[10] *Sir H. Lamb, Hydrodynamics, Chap. XI (Dover, New York 1879, sixth edition 1932, first American edition 1945).*

**R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.*

and where μ is the coefficient of viscosity. After making the appropriate expansions and evaluating the necessary integrals needed in the Lagrangian, the following equation of motion was obtained.*

$$\frac{4\pi\rho a^3}{n(2n+1)} \ddot{a}_n + \frac{8\pi(n-1)}{n} \dot{a}_n + \frac{4\pi(n-1)(n+2)\gamma}{(2n+1)} a_n = -\frac{\partial U_E}{\partial a_n} . \quad (13)$$

As pointed out by many of the earlier workers, such as Brazier-Smith et al,[5] the n = 2 mode dominates, and it is necessary to study only this fundamental oscillation mode in order to determine its stability. For this n = 2 case, equation (13) reduces further* as follows.

For the $n = 2$ case one may consider the time average of the electric field to be

$$E^2 = \frac{E_o^2}{2}\left[1 + 2\ m\ \cos\omega t\right] \qquad \left[\begin{array}{l}\text{a dc term and an ac term}\\ \text{at the modulation fre-}\\ \text{quency } \omega/2\pi \text{ and modula-}\\ \text{tion index m}\end{array}\right] \quad (14)$$

and

$$K^2 = \frac{E_o^2 a}{24\pi\gamma} , \left(\omega_2^o\right)^2 = \frac{8\gamma}{\rho a^3} \qquad \left[\begin{array}{l}\text{the mechanical frequency}\\ \text{of the drop}\end{array}\right] \quad (15)$$

$$\Gamma_2 = \frac{10\mu}{\rho a^2} , \quad u_2 = \frac{a_2}{a} , \text{ and } u_4 = \frac{a_4}{a} .$$

Then equation (13) can be expressed by

$$\ddot{u}_2 + \Gamma_2 \dot{u}_2 + \left(\omega_2^o\right)^2 u_2 = \left(\frac{9}{4}\right)\left(\frac{\varepsilon-1}{\varepsilon+2}\right)^2 \left(\omega_2^o\right)^2 (1 + 2m \cos\omega t) K^2$$

$$\times\left[1 + \frac{4(37\varepsilon-52)}{35(\varepsilon+2)} u_2 + \frac{28(\varepsilon+2)}{3(3\varepsilon+4)} u_4\right] . \quad (16)$$

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[5] *P. R. Brazier-Smith, M. Brook, J. Latham, C. P. R. Saunders, and M. H. Smith, Proc. Roy. Soc. A* 322 *(1971), 523.*

**R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.*

In order to obtain approximate amplitudes for water drops as a function of power in the laser beam, the u_4 terms in equation (16) were neglected* giving

$$\ddot{u}_2 + \Gamma_2 \dot{u}_2 + \omega_2^2 u_2 = \frac{9}{4} \omega_2^2 K^2 \left(\frac{\varepsilon-1}{\varepsilon+2}\right)^2 (1 + 2m \cos\omega t)$$

where

$$\omega_2^2 = \left(\overset{o}{\omega_2}\right)^2 \left[1 - \frac{9K^2}{35} \frac{(\varepsilon-1)^2 \quad (37\varepsilon - 52)}{(\varepsilon+2)^3}\right] .$$

The solution* of equation (17) is

$$u_2(t) = \frac{9}{4} K^2 \left(\frac{\varepsilon-1}{\varepsilon+2}\right)^2 \left[1 + 2 m Q_2 \cos(\omega t - \phi)\right] \qquad (18)$$

where

$$Q_2 = \frac{\omega_2}{\Gamma_2} , \; \phi = \cos^{-1}\left(\frac{\Gamma_2}{\omega_2}\right) ,$$

and

$$\omega = \sqrt{\omega_2^2 - \Gamma_2^2} .$$

Using the above solution, one finds that if, for example, a CO_2 beam of intensity 100 W/cm^2 is beamed onto a 2-μm-radius water drop of surface tension γ = 75 dynes/cm, the amplitude of the distortion, au_2 is 2×10^{-12} cm. Such a small value suggests that any frequency component in the light scattered from small droplets driven by a relatively low powered laser would not be detected. In order to be detected, the oscillation amplitude caused by the oscillating electric field would necessarily have to be larger than the amplitude of oscillation in the n=2 mode caused by thermal vibrations, which is $a_2 = (5\ kT/16\ \pi\tau)^{\frac{1}{2}}$ or about 1Å at 300 K($k = 1.38044 \times 10^{-16}$ ergs/k). Additional results are given below.

R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus used in this study consisted of (1) a means of illuminating a column of liquid drops with a modulated, cw, CO_2 laser beam, (2) a means of generating, containing, and measuring the drops, (3) a means of illuminating the liquid drops with a He-Ne laser beam and of detecting the scattering of this beam from the drops, and (4) a means of signal processing in order to detect extremely small signals. A discussion of these various subsystems is given in the appendices where it is also shown that ac signals of power levels between 10^{-16} to 10^{-17} W of 0.6328-μm radiation could be detected.

A forward-scattering experiment was conducted that lacked sufficient sensitivity to allow such small ac signals to be detected. Hence, in most of the experiments, the CO_2 and He-Ne lasers were aligned collinearly as shown in figure 1. A 4-mm-diam CO_2 beam, collimated and polarized in the vertical plane, was passed into the electro-optical modulator. A modulated CO_2 beam, polarized in the horizontal plane, emerged from the modulator and was brought to a focus in the fog chamber. An electric field of about 275 V/cm in amplitude acted on the drops in the vicinity of the focus point (this corresponds to a power density of 100 W/cm^2). This focus point was about 4.5 in. (114.3 mm) beyond the exit polarizer of the modulator. A small part of the CO_2 beam, $<$ 15 percent, was split off the main beam and was monitored during the course of the experiments by the photoconductive HgCdTe detector described in appendix A. The intensity modulation index of the CO_2 laser beam, as defined in appendix B, was measured to be between 20 to 45 percent over the frequency range from 10^4 to 3×10^6 Hz with a faster and more sensitive photovoltaic HdCdTe detector.

Figure 1 also shows that the He-Ne light was passed collinearly with the CO_2 laser beam through the focus point of the CO_2 laser light. Alignment of the beams was accomplished by allowing the CO_2 laser to burn small apertures ($<$ 1 mm in diameter) at the exit and entrance openings to the fog chamber and the He-Ne light was made to center on these apertures.

A 0.75-in. (19.0 mm) hole was cut in the fog chamber wall perpendicular to the focussing region of the CO_2 laser beam. A laminar flow of air directed past this opening prevented aerosol drops from collecting on the surface of the photomultiplier tube (PMT), which was 6 cm from the focus point, as shown in figure 1. The He-Ne light scattered from the drops in the vicinity of the CO_2 laser beam focus was then collected by the PMT.

After the CO_2 and He-Ne beams were aligned and the fog was introduced into the fog chamber, scattered He-Ne light was observed. The intensity of the scattered light typically was about 4×10^{-11} W.

This estimation of the power corresponds to an anode current of 10^{-7} A. The spectrum analyzer was generally set at -70 dBm and the resolution was set at 200 Hz. Data were recorded in not more than 5×10^4 Hz intervals and the signal was averaged at least 10^{13} times at each data point which gives about a 39-dB improvement in the signal-to-noise ratio. An acousto-optic modulator was used to modulate the He-Ne light, which scattered from the drops, as a check to see that the detection system was working properly over the entire modulation frequency range before and after each experiment.

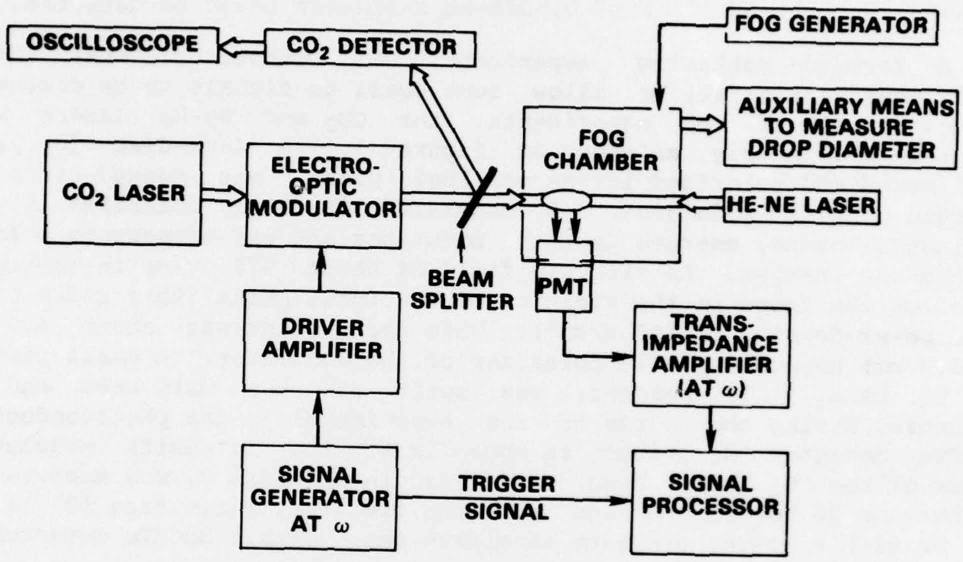

Figure 1. Schematic diagram of equipment used in water-drop experiment.

4. RESULTS AND DISCUSSION

No amplitude modulation of the He-Ne scattered light was observed in the frequency range from 4×10^4 to 3×10^6 Hz. This frequency range corresponds to the mechanical oscillation frequencies of drops varying in radius from about 21.2 to 1.19 µm. According to the measurements made with the Royco particle-size measuring device described in appendix C, about 60 percent of the water drops had radii that measured from 2.5 to 6 µm. These water drops have mechanical oscillation frequencies in the range covered in the experiment but might be too small for practical measurements as the calculated results will show.

Since no ac signal was observed in this experiment, where the relatively sensitive experimental equipment was used (described in appendices A to F), it is of particular interest to examine the results of the calculations. It should be mentioned that these calculated results were obtained using a model developed in a theoretical effort* paralleling this work that suggests that the distortion of small drops by laser beams will be difficult. Earlier workers have reported† that drops as small as 20 μm have been observed to elongate sufficiently to explode in electric fields of strengths comparable to those transmitted by more powerful laser beams (about 10 kV/cm) and that drops smaller than 3 mm can be caused[6] to explode in oscillating electric fields at lower field strengths than for the static case. The field carried by the CO_2 beam in this work, however, was relatively weak, and at the focus region of the CO_2 beam, the amplitude of the electric field was about 275 V/cm (this corresponds to the measured power density of 100 W/cm^2).

In making these calculations by evaluating equation (17), it was assumed that ka is small or that $\lambda \gg a$, where $k = 2\pi/\lambda$, λ corresponds to the wavelength of the electromagnetic radiation acting on the drop, and a is the radius of the drop. Also, the calculations were made using the coefficient of viscosity = 0.1 poise and an electric field strength of 275 V/cm (intensity of 100 W/cm^2). However, the distortion of the drop radius scales linearly with the power density throughout the tables (or as the square root of the applied electric field). For example, if the distortion of the radius is given as 10^{-10} m in the tables, an increase in the power density by a factor of 10 will result in the distortion being 10^{-9} m.

The results of the calculations made using a dielectric constant for water, ε, equal to 1.39 ($\varepsilon = 1.18^2$ for $\lambda = 10.6$ λm) are given in table I and are valid for drops of radius < 1.687 μm. For such small drops, the maximum change in the radius is too small to be detected with this equipment, being of the order 10^{-14} m. Since measurements were made over the frequency range corresponding to the mechanical frequencies of drops varying in radius from 1.19 to 21.2 μm, a calculation was made for the case of water drops in alternating electric fields corresponding to the mechanical frequencies of larger drops, and these results are given in table II. This case, called the near static case, corresponds to case 2 mentioned earlier, where the electric field is applied by parallel, conducting plates. In this case, the dielectric constant used for water was 78.2, and ka is small for all values of a that are considered.

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[6]*J. J. Billings and D. F. Holland, J. Geophys. Res. 74 (1969), 6884.*

**R. P. Leavitt, C. A. Morrison, and D. E. Wortman, unpublished data.*

†*See first entry of Selected Bibliography.*

TABLE I. MECHANCIAL OSCILLATION FREQUENCY OF FUNDAMENTAL MODE FOR WATER DROP AND CALCULATED CHANGE IN RADIUS, WHICH DROP UNDERGOES IN ALTERNATING ELECTRIC FIELD OF AMPLITUDE 275 V/cm

Note: The dielectric constant, surface tension, and viscosity coefficients for water used in the calculation are $\varepsilon = 1.39$, $\tau = 75$ *dyne/cm, and* $\mu = 0.1$ *poise.*

Drop Radius (μm)	Mechanical Frequency (MHz)	Change of Drop Radius (μm)
1	3.90	2.2×10^{-9}
1.1	3.38	2.7×10^{-9}
1.2	2.97	3.4×10^{-9}
1.3	2.63	4.2×10^{-9}
1.4	2.35	5.0×10^{-9}
1.5	2.12	6.0×10^{-9}
1.6	1.93	7.0×10^{-9}
1.7	1.76	8.1×10^{-9}
1.8	1.61	9.4×10^{-9}
1.9	1.49	1.1×10^{-8}
2.0	1.38	1.2×10^{-8}

TABLE II. MECHANICAL OSCILLATION FREQUENCY OF FUNDAMENTAL MODE FOR WATER DROP AND CALCULATED CHANGE IN RADIUS, WHICH DROP UNDERGOES IN ALTERNATING ELECTRIC FIELD OF AMPLITUDE 275 V/cm

Note: The dielectric constant, surface tension, and viscosity coefficient for water used in the calculation are ε = 78.2, τ = 75 dynes/cm, and μ = 0.1 poise.

Drop Radius (μm)	Mechanical Frequency (Hz)	Elongation of Drop Radius (μm)
1.0	3.90×10^{6}	1.5×10^{-7}
1.2	2.97×10^{6}	2.4×10^{-7}
1.4	2.35×10^{6}	3.5×10^{-7}
1.6	1.93×10^{6}	4.9×10^{-7}
1.8	1.61×10^{6}	6.6×10^{-7}
2.0	1.38×10^{6}	8.6×10^{-7}
3.0	7.50×10^{5}	2.4×10^{-6}
4.0	4.87×10^{5}	4.8×10^{-6}
5.0	3.49×10^{5}	8.5×10^{-6}
6.0	2.65×10^{5}	1.3×10^{-5}
7.0	2.10×10^{5}	2.0×10^{-5}
8.0	1.72×10^{5}	2.7×10^{-5}
9.0	1.44×10^{5}	3.7×10^{-5}
10.0	1.23×10^{5}	4.8×10^{-5}
20.0	4.36×10^{4}	2.7×10^{-4}
30.0	2.37×10^{4}	7.5×10^{-4}
40.0	1.54×10^{4}	1.5×10^{-3}
50.0	1.10×10^{4}	2.7×10^{-3}
100.0	3.90×10^{3}	1.5×10^{-2}

A comparison of the change in water drop radius for the two cases given in tables I and II shows that the second case gives a larger drop distortion at a given electric field strength. Equation 17 shows that the reason for this is the much larger dielectric constant for water in the second case.

In addition, the results of table II can be used in conjunction with the intensity calculations to determine the power and drop size requirements needed to cause large enough oscillation amplitudes to produce modulated signals for the scattered He-Ne light.

Calculations have been made by R. Barber* for variously sized, spherically shaped water drops to estimate the oscillation amplitudes of the drops necessary to produce detectable modulation of the scattered He-Ne light. From these calculations it was estimated that scattering from the drops undergoing a 0.5-percent change in radius for the 15-μm drops would produce modulated signals that could be detected by the equipment described earlier and shown in figure 1. Smaller sized drops would not give detectable ac signals. These estimates also yield that variations in the backscattering are more sensitive to radius changes of the drop than is the scattering for the more forward angles. A 13-percent change in the intensity of the backscattered light, for example, was calculated for a change of 7 Å in the radius of a 15-μm water drop. This compares with a 5-percent change in intensity at 90 deg for this case. An explicit solution for the scattering coefficients for ellipsoids has not been obtained[8,11] except for special cases, and so calculations are presently underway to obtain additional estimates for the scattering from oscillating water drops.

Since other workers, such as Billings and Holland[6] studied larger size water drops than were generated in these experiments, calculations were extended to drops of larger radii for comparison with these earlier measurements. The results of these calculations, where $\varepsilon = 78.2$ and $ka >> 1$, are given in table III. Since the elongation of the drop is assumed to increase linearly with the power density (or as the square root of the electric field), additional calculations were made for the case that the electric field is varied while the amplitude of the drop distortion and volume are held fixed. Results of these calculations are given in table IV for the near static case where the

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[6] *J. J. Billings and D. F. Holland, J. Geophys. Res. 74 (1969), 6884.*

[8] *P. W. Barber and D. S. Wang, Applied Optics 17 (1978), 797.*

[11] *M. Kerker, The Scattering of Light and Other Electromagnetic Radiation (Academic Press, New York 1969).*

**Private communication.*

TABLE III. MECHANICAL OSCILLATION FREQUENCY OF FUNDAMENTAL MODE FOR WATER DROP AND CALCULATED CHANGE IN RADIUS, WHICH DROP UNDERGOES IN ALTERNATING ELECTRIC FIELD OF AMPLITUDE 275 V/cm

Note: The dielectric constant, surface tension, and viscosity coefficient for water used in the calculation are $\varepsilon = 78.2$, $\tau = 75$ dynes/cm, and $\mu = 0.1$ poise.

Drop Radius (mm)	Mechanical Frequency (Hz)	Elongation of Drop Radius (μm)
0.25	986	0.15
0.50	349	0.85
0.75	190	2.33
1.0	123	4.78
1.2	93.8	7.55
1.4	74.4	11.10
1.6	60.9	15.49
1.8	51.0	20.80
2.0	43.6	27.07
2.2	37.8	34.35
2.4	33.2	42.70
2.6	29.4	52.16
2.8	26.3	62.77
3.0	23.7	74.59
3.2	21.5	87.65
3.4	19.7	102.0
3.6	17.3	126.0
3.8	16.6	134.7
4.0	15.4	153.1

TABLE IV. CALCULATED ELECTRIC FIELD STRENGTH REQUIRED TO DISTORT PROLATE SPHEROIDAL WATER DROP SO THAT RATIO OF MAXIMUM TO MINIMUM AXIS RATIO b/a = 2 FOR STATIC AND NEAR-STATIC CASES.

Note: The static case corresponds to an external electric field applied to the drop and the near static case corresponds to an alternating field applied at the fundamental mechanical frequency of the drop where $\varepsilon = 78.2$ *and* $ka \gg 1$.

Drop Radius (mm)	Electric Field for Near Static Case (kV/cm)	Electric Field for Static Case (kV/cm)
1	2.81	13.62
1.2	2.45	12.43
1.4	2.18	11.51
1.6	1.98	10.76
1.8	1.81	10.15
2.0	1.67	9.63
2.2	1.56	9.18
2.4	1.46	8.79
2.6	1.37	8.44
2.8	1.30	8.14
3.0	1.23	7.86
3.2	1.17	7.61
3.4	1.12	7.38
3.6	1.08	7.18
3.8	1.03	6.98
4.0	0.99	6.81

ratio of the major to minor axis of the prolate spheroidal drop is b/a = 2. In order to sustain a constant b/a = 2 value for this case, the electric field varies as $a_o^{-3/4}$ where a_o is the radius of the undistorted drop. Earlier calculations* for the static case (an applied dc electric field) showed that the electric field strength required to produce a constant b/a ratio varies as $a_o^{-1/2}$, and results for this case are also given in table IV. A comparison of the results calculated using both methods with the experimental results[6] is given in figure 2.

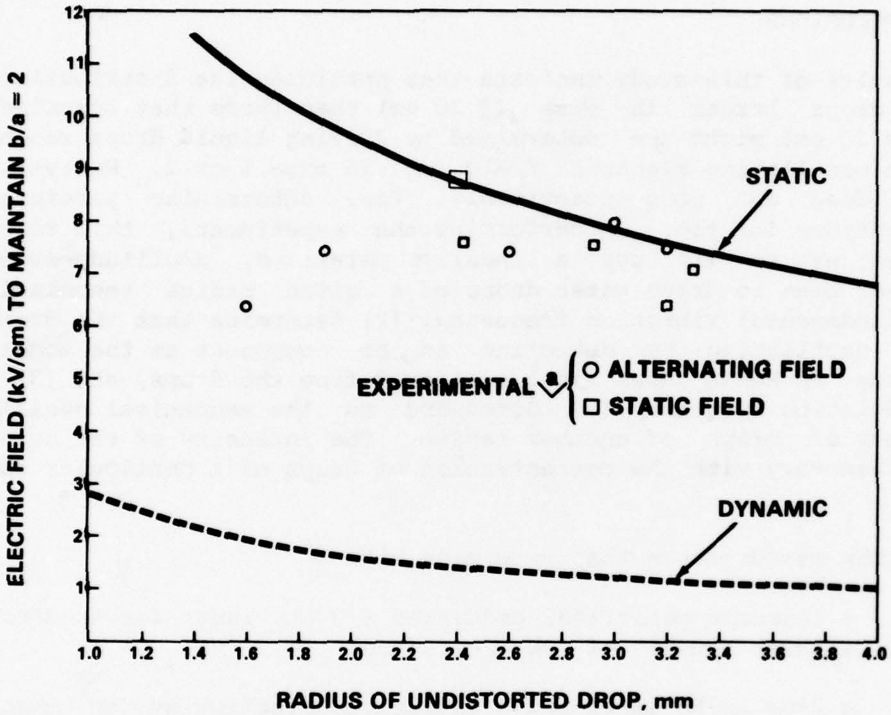

Figure 2. Electric field strength when drop's major axis to minor axis ratio equals 2 versus drop size for various electric fields.

Figure 2 illustrates that lower field strengths are required to distort the drops when they are driven at their mechanical resonant frequencies than are required in the static case. However, results of the calculations for the case where the drops are driven resonantly give the same distortions for the drops at lower electric fields as were reported by Billings and Holland.[6] Also, their experimental results show that drops smaller in radius than 2.4 mm distort to a b/a ratio equal to 2 at lower field strengths than for the larger size

[6]*J. J. Billings and D. F. Holland, J. Geophys. Res.* <u>74</u> *(1969), 6884.*
**See first entry of Selected Bibliography.*

drops. This is contrary to the calculated results for both the static case and the case where the drops are driven resonantly. Other workers, such as Taylor[2] report that water drops become unstable at b/a ratios < 2, and this condition could cause an error in the measurements. The experimental results, however, are close to the static dc field calculations whereas the calculated results for the oscillating drops yield distortions greater than reported[6] for drops of millimeter size.

5. CONCLUSIONS

Results of this study indicate that particle-size distributions for liquid drops larger in size ($\gtrsim$ 20 μm) than those that comprise most fogs (< 20 μm) might be determined by driving liquid drops resonantly with an oscillating electric field as in case 1 or 2. However, this method does not seem practicable for determining particle-size distributions for fog. In performing the experiments, this technique required us to (1) use a linearly polarized, amplitude-modulated CO_2 laser beam to drive water drops of a given radius resonantly at their fundamental vibration frequency, (2) determine that the drops are indeed oscillating by detecting an ac component at the modulation frequency in He-Ne laser light scattered from the drops, and (3) vary the modulation frequency to correspond to the mechanical oscillation frequency of drops of another radius. The intensity of the ac signal would then vary with the concentration of drops of a particular radius.

In the measurements that were made with

(a) a linearly-polarized, modulated 3-W CO_2 laser focussed to give a power density of 100 W/cm^2, and

(b) a 2-mW He-Ne laser and a sensitive detection system capable of measuring ac signals with intensities as low as about 10^{-17} W,

no ac signals were detected that corresponded to oscillating water drops of radii in the range 1.19 to 21.2 μm. This result is in line with the results of theoretical calculations that were also made, first, to determine oscillation amplitudes for the drops driven resonantly at their fundamental vibration frequency and, second, to determine scattering intensities made from drops of different radii and shapes. In the first calculation, it was found that the amplitude of oscillation for 20-μm radius drops, for example, is 2.7×10^{-10} m, and the oscillation amplitudes decrease for smaller drops as the 5/2 power of the radius. Since the calculated oscillation amplitudes scale

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[2] *Sir G. Taylor, Proc. Roy. Soc. London A 280 (1964), 383.*
[6] *J. J. Billings and D. F. Holland, J. Geophys. Res. 74 (1969), 6884.*

directly with the power density, slightly higher powered lasers would produce detectable oscillations in 20-μm drops, for example, but to obtain observable oscillations in 1-μm radius drops, one would require power densities greater than 10^7 W/cm^2, which would cause air breakdown and would vaporize the drops.[12]

Estimates of the required oscillation amplitudes needed to produce measureable ac signals were obtained from intensity calculations[8,11] of the light scattered as a function of angle, drop size, and, to some degree, drop shape. These intensity calculations are not presented in detail here since calculations are presently underway to determine better estimates for the scattering of laser light from oscillating water drops. However, the preliminary results indicate that radius changes of 0.5 percent for drops of radii greater than about 20 μm should be detectable according to the calculations and according to experimental results of other workers.[13] The calculations indicate that the backscattered light intensity changes[8,11] more with the drop radius and shape for the values of ka used here than it does at more forward angles. In addition, the calculated results for millimeter-sized water drops indicate that the drops driven resonantly may be distorted to the same b/a values in electric fields lower in amplitude than Billings and Holland[6] reported. Future studies of the light scattered from drops larger than 20 μm in radius between conducting plates will examine this point.

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[6] *J. J. Billings and D. F. Holland, J. Geophys. Res. 74 (1969), 6884.*

[8] *P. W. Barber and D. S. Wang, Applied Optics 17 (1978), 797.*

[11] *M. Kerker, The Scattering of Light and Other Electromagnetic Radiation (Academic Press, New York 1969).*

[12] *See, for example, S. L. Glicker, Appl. Optics 10 (1971), 644.*

[13] *E. J. Davis and A. K. Ray, J. Chem. Phys. 67, 414(1977).*

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APPENDIX A.--CO_2 LASER AND MODULATOR

In this experiment a model 941S GTE-Sylvania CO_2 laser was used to drive the liquid drops. The CO_2 laser head was adjustably mounted on an optical rail situated on a heavy workbench and aligned. The laser head contains a tube which provides a vertically polarized output beam of about 2.4 W, as measured by a Scientech model 362 power meter, in a TEM_{00} mode at a single wavelength near 10.6 μm. The output from the laser has a diameter of about 4 mm. A GTE-Sylvania model 750 water, heat exchanger was used during most of the experiment to cool the quartz cavity of the CO_2 tube for greater stability. The laser tube contained a piezoelectric tuning assembly that holds the mirror. By adjusting a regulated 0- to 1500-V power supply to operate the piezoelectric stack, the cavity length could be changed and different wavelength CO_2 lines could be selected. The maximum power that could be transmitted through the electro-optic modulator occurred at a wavelength of 10.6 μm because of the quarter-wave plate mounted on the modulator. The beam divergence should have been about 4 mrads, according to the 941S specifications.

The output from the cw, CO_2 laser was beamed into a GTE Sylvania model 410 CdTe modulator. This modulator varies the polarization angle of an incoming polarized beam at a rate equal to the frequency of the input signal. A Hewlett Packard model 651B test oscillator provided a sine wave for the modulator driver, which in turn applied a voltage across the CdTe crystal modulator. A quarter-wave plate followed this modulator and effectively biased it so that up to 45-percent intensity modulation resulted when only about 400 Vdc were applied to the CdTe crystal in the modulator unit. This biasing[1] by a quarter-wave plate, however, caused an effective insertion loss of 50 percent for the modulator unit. A polarizer (analyzer) followed the quarter-wave plate. A modulated signal of about 1.2 W was transmitted through the modulator unit. Alignment and operation of the modulator is described in appendix B.

The modulator unit itself consists* of a positive lens (made of zinc selenide and of focal length, $f_1 \simeq 1$ in.) which condenses the 4-mm beam to a diameter of about 2 mm. A negative lens ($f_2 \simeq 5$ or 6 mm) is then placed at the appropriate distance to pass a collimated beam through the CdTe crystal which has electrodes attached. A similar negative lens (f_2) and then positive lens (f_1) recollimates the beam. The latter two lenses act like a Galilean telescope in that their focal points coincide.

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[1] *A. Yariv, Quantum Electronics, New York, Wiley and Son, 2nd ed. (1975), 339.*

**C. Johnson of II-IV, Private Communication.*

APPENDIX A

About 1 W of the modulated CO_2 was passed through a beamsplitter (a flat piece of KRS5) and into the aerosol chamber. A small part of the beam reflected off the beamsplitter into a 0.5-mm square HgCdTe IR detector. This photoconductive IR device was cooled to liquid nitrogen temperature in a metal dewar, which limited its field of view to 60 deg. The SBRC specification report said that this detector has a D* of 2×10^{10} cm $(Hz)^{1/2}$/W at 10.6 μm when operated at a chopping frequency of 10^4 Hz. Next, the output from this detector, which was biased to operate with a detector current of 5 mA, was then displayed on a Tektronix 485 oscilloscope.

APPENDIX B.--ANALYSIS OF ELECTRO-OPTIC AMPLITUDE MODULATOR

An explanation of electro-optic modulation is given by Yariv.[1] A schematic diagram for a typical electro-optic amplitude modulator is shown in figure 14 of that reference (p 339). An addition analysis of that system has been worked out* and is given below.

Consider the incident $\vec{E}$ vector along the x-axis. The modulator resolves the $\vec{E}$ vector into components along x' and y', where

$$\hat{x}' = \frac{1}{\sqrt{2}}(\hat{x} - \hat{y}) \qquad \hat{x} = \frac{1}{\sqrt{2}}(\hat{x}' + \hat{y}')$$

$$\hat{y}' = \frac{1}{\sqrt{2}}(\hat{x} + \hat{y}) \qquad \hat{y} = \frac{1}{\sqrt{2}}(-\hat{x}' + \hat{y}')$$

and after passing through the modulator, the $\hat{x}'$ component picks up an extra phase relative to the $\hat{y}'$ component, so that

$$\vec{E} = \frac{1}{\sqrt{2}}\left(\hat{x}'\, e^{i\pi v/v_\pi} + \hat{y}'\right) .$$

Now the quarter-wave plate resolves these into new components where the unit vectors are given by

$$\hat{x}'' = \hat{x}' \cos\theta - \hat{y}' \sin\theta \qquad \hat{x}' = \hat{x}'' \cos\theta + \hat{y}'' \sin\theta$$

$$\hat{y}'' = \hat{x}' \sin\theta + \hat{y}' \cos\theta \qquad \hat{y}' = -\hat{x}'' \sin\theta + \hat{y}'' \cos\theta$$

and the $\hat{x}''$ component picks up an extra phase of $\pi/2$. Thus, after passing through the quarter-wave plate,

$$\vec{E} = \frac{1}{\sqrt{2}}\left[\hat{x}''\, e^{i\pi/2}\left(\cos\theta\; e^{i\pi v/v_\pi} - \sin\theta\right) + \hat{y}''\left(\sin\theta\; e^{i\pi v/v_\pi} + \cos\theta\right)\right] .$$

Expressing these in terms of x and y gives

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[1]A. Yariv, *Quantum Electronics*, New York, Wiley and Son, 2nd ed. (1975).

*R. P. Leavitt, private communication.

APPENDIX B

$$\vec{E} = \frac{1}{\sqrt{2}}\Big[(\hat{x}'\cos\theta - \hat{y}'\sin\theta)\, e^{i\pi/2}\left(\cos\theta\, e^{i\pi v/v_\pi} - \sin\theta\right)$$

$$+ (\hat{x}'\sin\theta + \hat{y}'\cos\theta)\left(\sin\theta\, e^{i\pi v/v_\pi} + \cos\theta\right)\Big]$$

$$\vec{E} = \frac{1}{\sqrt{2}}\Big\{\hat{x}'\Big[\left(\cos^2\theta\ \ e^{i\pi/2} + \sin^2\theta\right)e^{i\pi v/v_\pi} - \cos\theta\sin\theta\left(e^{i\pi/2}-1\right)\Big]$$

$$+ \hat{y}'\Big[-\sin\theta\cos\theta\left(e^{i\pi/2}-1\right)e^{i\pi v/v_\pi} + \left(\sin^2\theta\, e^{i\pi/2} + \cos^2\theta\right)\Big]\Big\}$$

or

$$\vec{E} = \frac{1}{2}\Bigg[\hat{x}\Big\{\Big[(\cos\theta - \sin\theta)\cos\theta\, e^{i\pi/2} + (\cos\theta + \sin\theta)\sin\theta\Big]e^{i\pi v/v_\pi}$$

$$+ \Big[-(\cos\theta - \sin\theta)\sin\theta\, e^{i\pi/2} + (\cos\theta + \sin\theta)\cos\theta\Big]\Big\}$$

$$+ \hat{y}\Big\{\Big[-\cos\theta(\sin\theta + \cos\theta)\, e^{i\pi/2} + \sin\theta(\cos\theta - \sin\theta)\Big]e^{i\pi v/v_\pi}$$

$$+ \Big[\sin\theta(\sin\theta + \cos\theta)\, e^{i\pi/2} + \cos\theta(\cos\theta - \sin\theta)\Big]\Big\}\Bigg]\ . \tag{B-1}$$

The polarizer then selects the y-component. The intensity is

$$I = E_y E_y^* = \frac{1}{4}\Big[-\cos\theta(\sin\theta + \cos\theta)e^{-i\pi/2} + \sin\theta(\cos\theta - \sin\theta)\Big]$$

$$\times\Big[-\cos\theta(\sin\theta + \cos\theta)e^{i\pi/2} + \sin\theta(\cos\theta - \sin\theta)\Big]$$

$$+ \frac{e^{i\pi v/v\pi}}{4}\Big[\sin\theta(\sin\theta + \cos\theta)e^{-i\pi/2} + \cos\theta(\cos\theta - \sin\theta)\Big]\Big[-\cos\theta(\sin\theta$$

$$+ \cos\theta)e^{i\pi/2} + \sin\theta(\cos\theta - \sin\theta)\Big]$$

$$+ e^{-i\pi v/v\pi}\left[\sin\theta(\sin\theta + \cos\theta)e^{i\pi/2} + \cos\theta(\cos\theta - \sin\theta)\right]\left[-\cos\theta(\sin\theta + \cos\theta) e^{-i\pi/2} + \sin\theta(\cos\theta - \sin\theta)\right]$$

$$+ \frac{1}{4}\left[\sin\theta(\sin\theta + \cos\theta)e^{i\pi/2} + \cos\theta(\cos\theta - \sin\theta)\right]\left[\sin\theta(\sin\theta + \cos\theta) e^{-i\pi/2} + \cos\theta(\cos\theta - \sin\theta)\right] .$$

The first and last terms combine to give

$$\frac{1}{4}(\cos^2\theta + \sin^2\theta)(\sin\theta + \cos\theta)^2 + \frac{1}{4}(\sin^2\theta + \cos^2\theta)(\cos\theta - \sin\theta)^2$$

$$= \frac{1}{4}(2\cos^2\theta + 2\sin^2\theta) = \frac{1}{2} ,$$

and the second and third terms give

$$\frac{e^{-i\pi v/v\pi}}{4}\left[-4\sin^2\theta\cos^2\theta - e^{i\pi/2}(\cos^2\theta - \sin^2\theta)\right] + \text{complex conj.}$$

$$= -2\sin^2\theta\cos^2\theta\cos\pi v/v_\pi - \frac{1}{2}(\cos^2\theta - \sin^2\theta)\cos\left(\pi v/v_\pi + \pi/2\right) .$$

Thus we have

$$\frac{I}{I_o} = \frac{1}{2} - 2\sin^2\theta\cos^2\theta\cos\left(\pi v/v_\pi\right) + \frac{1}{2}(\cos^2\theta - \sin^2\theta)\sin(\pi v/v_\pi) . \quad \text{(B-2)}$$

With the modulator off, the intensity is

$$\frac{I}{I_o} = \frac{1}{2} - 2\sin^2\theta\cos^2\theta = \frac{1}{2}\cos^2 2\theta ,$$

which reaches its maximum of 0.5 when $\theta = 0, \pm \pi/2$ or π.

With the modulator on and $V = V \sin x$, the average intensity is

$$\overline{I/I_o} = \frac{1}{2\pi}\int^{\pi} dx\ \frac{1}{2} - 2 \sin^2\theta \cos^2\theta \cos\left(\frac{\pi V_o}{V_\pi}\right)\sin x$$

$$+ \frac{1}{2}(\cos^2\theta - \sin^2\theta) \sin\left(\frac{\pi V_o}{V_\pi}\right)\sin x$$

The last term drops out.

We need

$$\int_{-\pi}^{\pi} \cos(a \sin x)\, dx = 2\pi\, J_o\, (a)$$

and obtain

$$\overline{I/I_o} = \frac{1}{2}\ 1 - 2 \sin^2\theta \cos^2\theta\ J_o\left(\frac{\pi V_o}{V_\pi}\right) = \frac{1}{2}\left(1 - \sin^2 2\theta\ J_o\left(\frac{\pi V_o}{V_\pi}\right)\right)$$

This yields

$$\frac{\bar{I}\ (\text{mod}) - \bar{I}\ (\text{no mod})}{\bar{I}\ (\text{no mod})} = \frac{\frac{1}{2}\left[1 - \sin^2 2\theta\ J_o\left(\frac{\pi V_o}{V_\pi}\right) - \cos^2 2\theta\right]}{\frac{1}{2}\cos^2 2\theta} = \tag{B-3}$$

$$\tan^2 2\theta\left[1 - J_o\left(\frac{\pi V_o}{V_\pi}\right)\right] .$$

The above relation means that the output intensity does not change when the modulator is turned on or off as long as the quarter-wave plate is rotated to give maximum transmission.

If one assumes that the quarter-wave plate is aligned for maximum transmission, as when $\theta = 0$, equation (B-2) becomes

$$\frac{I}{I_o} = \frac{1}{2}\left(1 + \sin\frac{\pi V}{V\pi}\right) .$$

With the modulator on and $v = v_m \sin \omega_m t$, this becomes

$$\frac{I}{I_o} = \frac{1}{2}\left(1 + \sin\frac{\pi v_m}{v_\pi} \sin \omega_m t\right) ,$$

which can be written

$$\frac{I}{I_o} = \sin^2\left(\frac{\pi}{4} + \frac{\Gamma_m}{2} \sin \omega_m t\right) . \qquad \text{(B-4)}$$

If $\Gamma_m = \pi v_m / v_\pi << 1$ this becomes $I/I_o \simeq \frac{1}{2}\left[1 + \Gamma_m \sin \omega_m t\right]$, which is the same as equation 14.3-8 in Yariv;[1] here Γ_m represents the modulation index and the modulation frequency is $f_m = \omega_m/2\pi$.

The intensity modulation can be defined for the case $\Gamma_m << 1$ as in Yariv.[1] Or, by using equation (B-4), we can define modulation index m = $\left[I(\text{mod}) - I(\text{no mod})\right]/I(\text{no mod})$. By choosing $\sin \omega_m t = 1$,

$$M = \frac{\sin^2\left(\frac{\pi}{4} + \frac{\Gamma_m}{2}\right) - \sin^2\left(\frac{\pi}{4}\right)}{\sin^2\left(\frac{\pi}{4}\right)}$$

The phase retardation for the CdTe crystal in this geometry is

$$\Gamma = \frac{2\pi\, N_o^3\, r_{41}\, LV}{\lambda d}$$

A. Yariv, Quantum Electronics, New York, Wiley and Son, 2nd ed. (1975).

where

N_o = index of refraction = 2.6

r_{41} = applicable electro-optic coefficient = 6.8×10^{-12} m/V

L = 50 mm

v = modulation voltage = 400 V

λ = operating wavelength = 10.6 μm

d = width of crystal = 3 mm

Γ = 0.472 radians = 27 deg.

The intensity modulation index, then, is M = 15 percent.

APPENDIX C.--LIQUID DROP GENERATORS, FOG CHAMBER, AND PARTICLE SIZING DEVICE*

**R. Doherty of ARRADCOM at Edgewood Arsenal provided and operated most of the drop generation and measuring equipment. He was primarily responsible for determining the particle sizes and concentrations that were used in this experiment.*

Three separate methods were used to generate monodisperse liquid aerosols and then a polydisperse fog. Initial experiments used a Berglund-Liu monodisperse generator which produced olive-oil drops in diameters ranging from about 6 to 12 µm. Preliminary efforts were not successful in detecting modulated signals in the scattering from these drops, whose mechanical frequencies might vary from about 3×10^6 to 1.8×10^5 Hz (calculated by assuming $\gamma = 32$ dynes/cm). Consequently, this part of the experimental apparatus was replaced with a liquid water drop generator to obtain higher concentrations of drops in the size range of interest.

A means of generating monodisperse water drops was set up as shown in figure C-1. An AgCl crystal, which was placed in a ceramic boat within the quartz tube as shown in the figure, was heated in a furnace to 600 C. The AgCl nuclei, which were boiled off, were carried by a stream of N_2 gas to a glass condensing section. Steam, generated by a flask in a heating mantle, condensed on the AgCl centers to produce a stream of drops emanating from a 30-µm-diam tube. A constant fog was then formed in the fog chamber. About 30 percent of the drops varied in diameter from 10 to 12 µm. Another 30 percent were in the size range from 5 to 10 µm in diameter. In addition, the concentration was determined to be about 320 particles/cm^3.

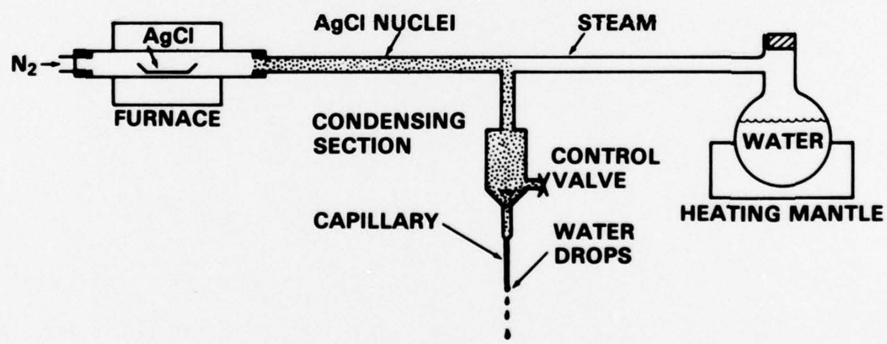

Figure C-1. Schematic diagram of equipment used to generate monodisperse water drops of radii approximately equal to 5 µm.

The particle-size and concentration measurements were made with a Royco Instrument device, module 508 with a model 225 counter. This device, which counts particles in five separate channels in ranges selected by the user, monitored the aerosols in most of the experiments.

APPENDIX C

Particle sizes and concentrations similar to those obtained by forming water drops on AgCl nuclei were found in the fog chamber when steam from the flask was simply directed into the fog chamber. Most of the scattering measurements were made by utilizing this simpler method to obtain a diameter size distribution of water drops in a range extending down to at least 2.38 μm (corresponding to a mechanical oscillation frequency of about 3×10^6 Hz, which is about the maximum frequency for the electro-optic modulator).

The dimensions of the fog chamber shown in figure 1, body of the report, were 30 × 15 × 40 cm ($\ell \times \omega \times h$). In every case the plastic walls of the chamber were covered with black paper and/or cloth to minimize the scattering of any extraneous light into the photomultiplier tube.

APPENDIX D.--ILLUMINATION SOURCE AND DETECTION MEANS

In carrying out this experiment, a Spectra-Physics model 133 He-Ne laser was aligned collinearly with the CO_2 laser and beamed onto the drops as is shown in figure 1, body of report. The randomly polarized output from this laser measured less than 2 mW, and the beam diameter measured about 2 mm. The beam divergence was expected to be about 1 mrad.

Since the distribution of the scattering from the oscillating drops as a function of angle was not known, an attempt to determine the extent of the modulated scattered signal was made by shining the He-Ne beam transmitted through the fog into an RCA 4459 photomultiplier tube (PMT). If the drops were not oscillating, the transmitted intensity, I, would be related to the intensity of the light incident on the water droplets by the expresion $I = I_o e^{-\tau \ell}$ where τ is the turbidity,[1] ℓ is the path length, and I_o is the incident intensity. If the droplets were oscillating, say at the modulation frequency, the time-varying cross-sections of the drops would scatter light into all angles. Hence, the transmitted signal would contain the modulation frequency. After preliminary efforts to see modulation of olive-oil droplets were not successful, this arrangement of the detection system was also changed to that shown in figure 1.

An RCA 4459 PMT was used as the detector. The usual operating voltage between the cathode and anode in this experiment was 1500 Vdc. The typical sensitivity at this voltage is 2 A/lumen and the current amplification is about 1.2×10^5; the dark current was measured to be about 0.58×10^{-10} A on a Keithley 417 picoammeter.

The output from the PMT was fed into a transimpedance amplifier (TIA). This TIA has a gain greater than 15 over the entire range from 4×10^4 to 3×10^6 Hz.

In the preliminary experiments, the output from this TIA was fed directly into a Tektronix 7A22 differential amplifier which was plugged into a Tektronix 7704 oscilloscope. In later experiments the output from the TIA was fed into a Tektronix 7L13 spectrum analyzer that was coupled to a PDP 11/15 computer through the 7704 oscilloscope system, and this signal processing is described in appendix E.

---

[1] *M. Kerker, The Scattering of Light and Other Electromagnetic Radiation (Academic Press, New York 1969).*

APPENDIX E.--SIGNAL PROCESSING

The most sensitive measurements were made by feeding the signal from the transimpedance amplifier (TIA) into the spectrum analyzer coupled to a PDP 11/15 computer. The 7L13 spectrum analyzer is a high performance instrument whose features include (1) greater than 70-dB dynamic range, (2) sensitivity down to -128 dBm, (3) resolution capability from 3 MHz to 30 Hz, (4) fully calibrated display modes of either 10 dB/div, 2 dB/div, or linear, (5) calibrated sweep spans from 100 MHz/div to 200 Hz/div, and (6) full range of video filtering for noise averaging. The 7L13 SA plugs into and operates with a 7704 A oscilloscope system that allows the signal to be stored and averaged.

The signal from the spectrum analyzer was converted from analog to digital and stored. The analog-to-digital converter takes a horizontal and vertical sample every 6.5 μs. For sweep speeds slower than 0.5 ms, all 512 locations (horizontal sample of 9 bits) are filled on one sweep. The vertical sample contains 10 bits or 1024 points.

In an attempt to further improve the sensitivity of the system, the signal from the spectrum analyzer was averaged. This averaging technique removes uncorrelated noise from repetitive signals that are synchronously triggered. If this signal is sampled at the same points, then the average value of the time-accumulated samples at each point will be equal to the actual value of the waveform at each point. If this signal is corrupted with noise whose long-term average is zero but can still be synchronously triggered, the average value of the time-accumulated samples at each point on the noise-corrupted signal will approach the value of the noise-free signal at each sample point. As more samples are averaged, the signal-to-noise ratio is increased by the $\sqrt{M}$, where M is the number of averages. If M is expressed as a power of 2, then the improvement in signal-to-noise ratio will correspond to 3 dB per power of 2. A maximum number of averages for the system was found to be 32,759 (2^{15} = 32,768), which is nearly a 45-dB improvement in signal-to-noise ratio. Thus, a signal too small to be detected by using the 7L13 spectrum analyzer alone could be detected by this signal-processing technique.

APPENDIX F.--SENSITIVITY OF DETECTION SYSTEM FOR SCATTERED He-Ne LIGHT

In order to determine the sensitivity of the detection system for measuring small signals, the equipment was set up as shown in figure F-1. The power in the modulated He-Ne beam that was incident on the first glan polarizer measured 0.6 mW with a Scientech-162 powermeter. The modulation index of this beam was determined to be about 0.05, which corresponds to one-half the peak-to-peak value of the ac signal divided by the dc voltage where the output from the Photomultiplier Tube (PMT) was terminated across a $10^4\ \Omega$ load. The transmission of each glan prism (polarizer) was measured to be 35 percent on a Cary 14 spectrophotometer. The transmission of the two polarizers was further reduced by rotating the optic axis of the second polarizer with respect to the first. If θ describes the angle between the optic axes of the polarizers, with $\theta = 0$ deg giving complete extinction, the intensity through these varies as $\sin^2\theta$. Light transmitted through the polarizers then was passed through a Corning CS7-57 filter, which measured 0.286-percent transmission of the He-Ne light. The beam diameter of the light through the filter was about 2 mm, and it was incident on a 0.152-mm-diam aperture placed in front of the PMT. By changing the angle 1 deg away from complete extinction of the light through the crossed polarizers, a signal could be easily seen on the spectrum analyzer. These data translate into a detectable signal of 1.8×10^{-14} W $[0.6 \text{ mW} \times (0.35)^2 \times \sin^2 1^0 \times 0.05 \times 2.86 \times 10^{-3} \times (0.152/2)^2]$. The modulation index was then lowered by changing the input signal into the modulator, until the signal could not be seen on the spectrum analyzer. A 20-dB change could yet be detected easily by signal averaging 2^8 times. This corresponds to a detectable signal of about 10^{-16} W.

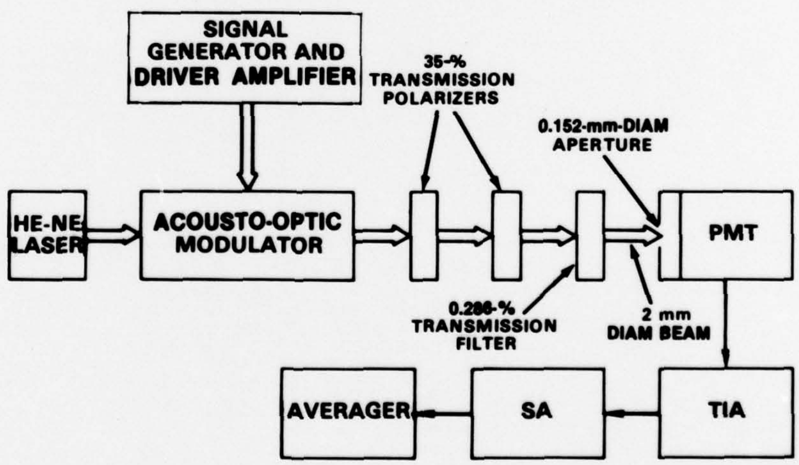

Figure F-1. Schematic diagram of equipment used to test sensitivity of detection system. (Amplitude-modulated signals of 0.6328-μm wavelength He-Ne light could be detected with this system.)

APPENDIX F

As a check on this detection sensitivity for small signals, the modulation index was again adjusted to 0.05. The polarizers were adjusted to give a current of 6×10^{-10} A as measured on the picoammeter. Since the gain is about 1.2×10^5, this will give $[6 \times 10^{-10}$ (anode current)$]/1.2 \times 10^5$ (gain) $= 5 \times 10^{-15}$ A as the cathode current. An S-20 surface has a typical sensitivity of 25 mA/W; hence, $(5 \times 10^{-15})/25 \times 10^{-3}$ W $= 2 \times 10^{-13}$ W. But the modulation index is 0.05 which gives a value of 10^{-14} W producing the ac signal observed on the spectrum analyzer. Again this signal could be reduced by 20 to 30 dB and yet be detected by signal averaging. Thus, the minimum detectable signal seems to be between 10^{-16} and 10^{-17} W. This corresponds to the power carried by 10^2 or 10^3 photons/s since the energy of a photon of wavelength 0.6328 μm equals 3.14×10^{-19} joules ($w = h\nu = hc/\lambda$).

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