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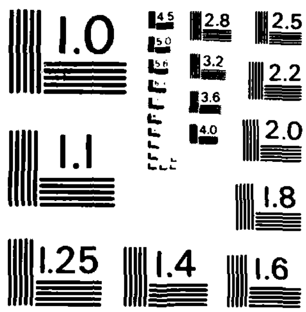

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Topically Classified Bibliography on Shapes of Falling Drops, Drops in Electric Fields, and Related Topics

by Clyde A. Morrison
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Harry Diamond Laboratories
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We report results of an extensive literature search on shapes of falling drops, drops in electric fields, and related topics. Numerous references to the literature from the late nineteenth century through the present are given.

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PREFACE

In an informal discussion with the authors on 28 April 1982 of the previous work done by Harry Diamond Laboratories (HDL) for the Chemical Systems Laboratory (CSL) concerning drop oscillation and scattering, Dr. Edward Stuebing expressed an interest in the possibility of our doing a bibliographic search at HDL. We were funded by CSL soon thereafter to proceed with such a search. The present publication is the result.

Since our experience at HDL has been in the determination of the shape of liquid drops, it is not surprising that the most complete parts of this bibliography deal with that and closely related subjects.

When reading over the papers in order to categorize them, we discovered a number of unsolved problems related to particular topics. One of these problems (that of a charged liquid drop in the presence of a point charge) was written up and is to be published in the proceedings of the 1982 CSL Scientific Conference on Obscuration and Aerosol Research. Several other problems are presently in incomplete stages of development at HDL.

The automated sources used for the search were on-line systems: Defense Technical Information Center (DTIC); Lockheed's Dialog; and Systems Development Corporation's Orbit (SDC) back to 1970. For work done before 1970 the Chemical Abstracts and Physics Abstracts were used. Also, the Dissertation Abstracts were searched, on line (the listing goes back to 1861). The approximate cutoff date was 15 November 1982. Not all of the papers found in the search are included and many papers not found in the search were included. This was prompted by reading the papers selected from the automated search and then proceeding to find pertinent papers referenced therein.

A complete set of copies of all numbered references given in the bibliographic subsections of each chapter has been collected by the authors and delivered to Dr. Edward Stuebing at CSL (for books the title page, giving date of publication and publisher, and the table of contents were copied). These copies are numbered according to the reference listings.

The bibliography is arbitrarily divided into 12 sections. The first section is further divided into two separate bibliographies (work done at HDL and work done elsewhere). Each division has an introductory section called "overview" which contains what we considered the most important results reported in the papers listed in that section. The overview also contains cross references to other sections of the bibliography and these cross references are indicated. None of the sections of this bibliography should be taken as exhaustive, as the selection of references included here was made at the authors' discretion. In particular, the section titled "Electromagnetic Scattering from Particles and Drops" if exhaustive would be much larger than this entire bibliography! However, we hope that this bibliography will serve for some use at least as a starting point for any in-depth investigation.

We wish to thank the entire library staff and in particular Norman Brandt, without whose help this work would have been impossible. We also thank Jessica Putnam for her excellent typing of the manuscript. Their dedication and effort was well beyond the call of duty.

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1. STATICS AND DYNAMICS OF DROPS

1.1 Work done at Harry Diamond Laboratories

1.1.1 Overview

The earliest work done at Harry Diamond Laboratories (HDL) consisted of a sequence of limited-circulation informal reports (1977, 1-4). The result obtained in the third report (1977, 3) formed the basis of two publications (1980, 1981) that give the equations that determine the shape of a drop in an electric field. The theory developed in all the above reports and publications allowed the drop in the presence of an electric field to freely distort from a sphere into a shape determined by minimizing the total energy, surface plus electrostatic. The variables of minimization are the coefficients of an expansion of an arbitrary point on the surface in Legendre polynomials.

The usual approach to the problem of the shape of a drop in an electric field is to assume that the drop is spheroidal (an ellipse of revolution along the direction of the electric field). The parameters describing the spheroid are then determined by minimizing the electrostatic and surface energy simultaneously.

Both of the above procedures can be implemented for arbitrary dielectric constants for the drop and the surrounding medium. Thus a comparison of the two procedures can be made and a definite limit set on where the spheroidal approximation ceases to be meaningful.

1.1.2 Bibliography

Informal In-House Documents

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4. Morrison, C. A., D. E. Wortman, and N. Karayianis, Scattering caused by oscillating drops (February 1977).

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1. STATICS AND DYNAMICS OF DROPS

Publications

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1.2 Other Work

1.2.1 Overview

The earliest (or at least the most successful) attempt at the calculation of the drag on a spherical drop in a viscous fluid was done by Stokes (1851, not included here). Stokes' result for the drag force on a sphere is

$$F_d = 6\pi\eta a U \quad , \tag{1}$$

where η is the viscosity, a the sphere radius, and U the velocity. The result of Stokes' calculation was used much later by Millikan in interpreting the data in his famous oil drop experiment. The first attempt at corrections to Stokes' result appears to have been carried out by Oseen and is reported in his book (1927), but the original work appears much earlier (1911, not included here). Oseen's result arises from an approximate correction to the Navier-Stokes equation and is

$$F_d = 6\pi\eta a U\left(1 + \frac{3}{8}\,\frac{\rho a|U|}{\eta}\right) \quad , \tag{2}$$

where ρ is the density of the fluid and the other quantities are as given in equation (1).

Most textbooks on hydrodynamics include a derivation of Stokes' formula. Two excellent derivations are given in Page (1935) and Landau and Lifshitz (1959). Page also includes an analysis of a sphere in a perfect fluid ($\eta = 0$) and contrasts the result with that obtained when viscosity is included. Landau and Lifshitz, besides giving a derivation of Stokes' result, give partial results for a number of related topics in the form of problems. The book written by Lamb (1945, Dover reprint) is a wealth of information on related problems. In particular, he writes the generalized drag on an ellipsoid in a fluid of viscosity η as

$$F_d = 6\pi\eta RU \quad , \tag{3}$$

where U is the velocity in the x-direction, and the equation for the ellipsoid is given by

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad .$$

The quantity R is given by

$$R = \frac{8}{3} \frac{abc}{\chi_0 + \alpha_0 a^3} \quad , \tag{4}$$

where

$$\chi_0 = abc \int_0^\infty \frac{d\lambda}{\Delta} \quad ,$$

$$\alpha_0 = abc \int_0^\infty \frac{d\lambda}{(a^2 + \lambda)\Delta} \quad ,$$

and

$$\Delta = \left[(a^2 + \lambda)(b^2 + \lambda)(c^2 + \lambda)\right]^{1/2} \; .$$

For a disc the result given in equation (4) gives

$$R = 8c/\pi \tag{5}$$

for the plane of the disc perpendicular to the x axis and

$$R = 16c/9\pi \tag{6}$$

for the plane of the disc parallel to the x axis.

Goldstein (1938) gives corrections to Stokes' and Oseen's earlier corrections in the form (corrected by Shanks (1955))

$$C_D = \frac{6\pi}{R}\left(1 + \frac{3}{8}R \frac{19}{320}R^2 + \frac{71}{2,560}R^3 - \frac{30,179}{2,150,400}R^4 + \frac{122,519}{17,203,200}R^5\right) \quad , \tag{7}$$

where $R = Ua/\nu$, U is the velocity of flow, and ν is the viscosity.

More recently Proudman and Pearson (1957) obtained corrections to Stokes' result in the form

$$C_D = \frac{6\pi}{R}\left[1 + \frac{3}{8}R + \frac{9}{40}R^2 \ln R + O\left(R^2\right)\right] \quad , \tag{8}$$

with R the same as in equation (7). This latter result seems to be the latest attempt at improving Stokes' original result. In all the above work the sphere, or ellipsoid, was considered to be a fixed shape. That is, the flow of the fluid around the body was assumed not to change the shape of the body.

The problem of a fluid sphere of density ρ and viscosity η in a flowing fluid of density ρ' and viscosity η' seems to have been attacked simultaneously by Hadamard (1911, not included here) and Rybczynski (1911). The resulting drag is given by

$$F = 3\pi\mu\eta' R(3\eta' + 2\eta)/(\eta + \eta') \quad , \tag{9}$$

where R is the radius of the sphere. Landau and Lifshitz (1959) discuss the limitations of equation (9), which places an upper limit on R such that the drop remains spherical. The resulting terminal velocity for the drop considered in equation (9) is given by

$$v = 2R^2 g(\rho - \rho')(\eta + \eta')/[3\eta(2\eta + 3\eta')] \quad . \tag{10}$$

Almost all the liquid drop distortions were, when considered at all, in the form of ellipsoids of revolution about the direction of the flow. Of all the papers and books reviewed, only two papers considered the distortion of a drop in a general shape. The two papers, Reid (1960) and Chandrasekar (1959), considered general deformations but did not develop the details. It seems that no one has taken the original result of Rayleigh (1879) and extended the analysis to the case of a slightly distorted sphere in the flow of a viscous fluid (gas). More will be mentioned of this approach in section 2 (Drops in an Electric Field) and section 4 (Shape of Falling Drops).

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Pages 473-475. Oscillation of spherical drop of density ρ surrounding medium of density ρ' gives

$$\omega^2 = \frac{n(n - 1)(n + 1)(n + 2)\ T_1}{[(n + 1)\rho + n\rho']a^3}$$

($\rho' = 0$ gives Rayleigh's (1879) result). $\rho = 0$ gives bubble surrounded by liquid $\omega^2 = (n + 1)(n - 1)(n + 2)T_1/\rho'a^3$.

Page 450. Oscillations of a drop held together by gravity.
Page 452. Normal coordinate analysis of above.
Page 453. Drop (ocean) with rigid core held by gravity (normal coordinate treatment).
Page 599. Slow motion of a sphere in viscous fluid. Stokes' formula.
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Page 25, Problem 2. A solid rigid sphere moving through an incompressible ideal fluid (no viscosity).
Page 29, Problem 8. An expanding sphere (R = R(t)) in an incompressible ideal fluid.

Page 49. Table of kinematic viscosity, $\nu = \eta/\rho$. η is called the dynamic viscosity and ρ is the density.

Material	η (gm/cm s)	ν (cm^2/s)
Water	0.010	0.010
Air	0.00018	0.150
Alcohol	0.018	0.022
Glycerine	8.5	6.8
Mercury	0.0156	0.0012

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2. DROPS IN AN ELECTRIC FIELD

2.1 Overview

The earliest work on liquid drops in an electric field appears to be experimental. Among the earliest is the work of Wilson and Taylor (1925), although they refer to somewhat related earlier work: C. T. R. Wilson, Phil. Trans. A221 (1921), 104; Zeleny, Camb. Phil. Soc. Proc. 18 (1915), 71; and Zeleny, Phys. Rev. 10 (1917), 1 (not listed in bibliography). In their paper, Wilson and Taylor investigated the distortion of soap bubbles in an electric field and found that the field required to break a soap bubble is inversely proportional to the square root of the radius. That is, the critical field E_c is given by

$$E_c = c\sqrt{\gamma/r} \quad , \tag{11}$$

where $c \approx 1.61$ (cgs units) and γ is the surface tension. Nolan (1926) investigated the breaking of water drops by an electric field and found that the dependence of critical field on drop radius consists of two regions. If the radius is less than 0.2 cm, the critical field is given by equation (11) with appropriate constants. However, for drops larger than 0.2 cm, the critical field is proportional to $r^{-5/3}$.

Further significant investigations of drops in an electric field did not appear until the work of Thacher (1952), O'Konski and Thacher (1953), O'Konski and Gunther (1955), and O'Konski and Harris (1957). In all of these investigations, the shape of the drop is assumed to be spheroidal (ellipsoid of revolution about the field direction), and the deformation of the drop caused by the electric field is found by minimizing the electric and surface energies. The variable of minimization is the eccentricity of the spheroid. The last paper of O'Konski and Harris (1957) considered the case where both the drop and the external medium have different conductivities as well as different dielectric constants. They found the rather spectacular result that, for certain combinations of conductivities and dielectric constants, the sphere was undistorted, independent of the electric field strength.

Further work assuming a spheroidal deformation of liquid drops in an electric field was pursued by Taylor (1964, 1966). In his earlier work, Taylor (1964) dealt with two approximate forms; by adjusting certain constants in his solutions, he was able to predict regions of instability. In his later paper, Taylor (1966) showed that the result of O'Konski and Harris (1957) is physically untenable. He showed that if the assumptions of O'Konski and Harris were examined more closely, the stress predicted by their theory varied over the surface of the drop. To counteract this variation, Taylor proposed that the fluid both inside and outside the drop is in motion and gave the solution for the fluid motion such that the drop remained a sphere in the presence of an external field. Strangely, his result is again independent of electric field strength.

All of the above work involved the assumption that the drop or bubble is distorted by an electric field into a definite shape: a spheroid, i.e., an ellipsoid of revolution about the field direction. Garton and Krasucki (1964) solved the problem of the shape of a bubble in an insulating liquid with no geometrical restrictions on the particular shape. They found that for low values of electric field their results approximate a spheroidal shape, but for larger values the deviation from a spheroid was large; they nevertheless chose to devote the remainder of their analysis to small deviations.

The problem of finding the frequencies and the distortion of a drop in an electric field was attacked by workers at the University of Illinois, who used the method established by Rayleigh (1879; see sect. 1.2.2). The shape of the drop was determined by minimizing the total energy, surface plus electric, with respect to coefficients in an expansion of the radius in terms of Legendre polynomials. The early work of Hendricks and Schneider (1963) and Schneider (1964; see sect. 3.2) give the preliminary investigations and nomenclature used in the later work by Sample (1965), Sample and Hendricks (1969), and Sample, Raghupathy, and Hendricks (1970). This last work is very similar to the approach taken by workers at HDL as reported by Morrison, Leavitt, and Wortman (1979, 1980, 1981; see sect. 1.1.2). The result given by Sample et al (1970) is for conducting drops, while the work of Morrison et al (1979-1981; see sect. 1.1.2) is for drops of arbitrary dielectric constant and includes the former work when the dielectric constant is allowed to approach infinity.

Many of the later references given in the bibliography apply to the dynamics of spherical or spheroidal drops in an electric field. Characteristic of these references is the work of Davis (1962, 1964a, 1964b). More recent investigation of the dynamics of drops is given by Schlamp et al (1976, 1979).

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3. CHARGED DROPS

3.1 Overview

The first (and still the most quoted) work on charged liquid drops is the paper by Rayleigh (1882). In this early paper, Rayleigh showed that a liquid drop held together by surface tension and charged with electricity becomes unstable when the charge exceeds a certain value. Until very recently his criterion was applied not only to charged drops but also to drops in an electric field. Rayleigh's earlier work was augmented by his later paper (1916) concerning both cylindrical and spherical liquid drops. Unfortunately, in treating the spherical drops in this latter work he did not have available algebraic expressions for the integrals of three or more Legendre polynomials, which were being developed at the time his paper was written. The later work such as Schneider (1964) and Peters (1980) uses the original idea of Rayleigh (1882) but benefits from the modern developments of the theory of Legendre functions.

The effects of charges and fields on collisions of drops has been reported by Davis (1965) and Takahashi (1973).

Much of the work on charged drops and charged particles is contained in section 2 (Drops in an Electric Field).

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4. SHAPE OF FALLING DROPS

4.1 Overview

An early paper on this topic is one by Flower (1928). In his introduction, Flower covers many of the results of previous work and states that the first work pertaining to falling drops was by Lenard (1904). Flower also gives in his introduction a rather brief but complete description of the ingenious techniques employed by the earlier workers. Apparently, the paper was delivered at some sort of meeting, because there is a question and answer section at the end. This section is equally interesting in that many related earlier works are cited. In his paper, Flower measures the terminal velocity and the distance the drop travels in reaching that velocity. After determining the distance, z, for the drop to reach terminal velocity, Flower fits his data to the equation

$$z = c\left(1 - e^{-Bv}\right) \quad , \tag{12}$$

where v is the volume of the drop and c and B are constants to be determined to fit the data. The values of c and B found were 319.2 and 0.5527, respectively, for water and 348.2 and 1.142 for methyl salicylate. The terminal velocity was determined for a large variety of drop sizes, and the results are presented in tabular form along with comparative earlier results. In discussing his result, Flower is aware of Stokes' (1852, not included here) formula for the drag force on a sphere but interprets his result using a drag force proportional to the square of the velocity (Stokes' drag force is linear with velocity). Unfortunately, he was unaware of Oseen's (1910, not included here) correction to Stokes' result; it would be interesting to see how the data would have turned out using Oseen's expression for the drag force.

A book by Edgerton and Killian (1939) contains a large number of interesting high-speed photographs of drops in motion and colliding with plates. The report by Blanchard (1948) covers a large variety of observations on drops at terminal velocity. These observations include the oscillation frequency, shape, and rotation. Most of these results are presented in the form of photos and graphs. In his later papers, Blanchard (1950, 1951, 1955, 1962) expanded and presented in more detail the results reported in his 1948 work.

A rather sophisticated apparatus for measuring the terminal velocity is described by Gunn and Kinzer (1949), in which it is claimed that the experimental arrangement for measurements on drops does not disturb the drops in any way. Further detailed descriptions of the apparatus of Gunn and Kinzer are given in references in this paper. In a later paper, Gunn (1949) makes the observation that freely falling raindrops of mass near 0.5 mg move laterally as well as downward; raindrops of significantly different mass fall vertically. Gunn explained this peculiar behavior by an interference of the natural resonant frequency with the eddy current detachment frequency.

4. SHAPE OF FALLING DROPS

Spilhaus (1948) calculates the shape of raindrops falling at terminal velocity assuming a spheroidal shape of the raindrop and balancing the pressure at the surface of the raindrop. A moderate table of terminal velocity of raindrops as a function of the radius of the raindrop is given. Spilhaus' result is frequently quoted. Imai (1950) does a similar, but perhaps more rigorous, calculation and finds good agreement with the experimental measurements of Gunn and Kinzer (1949). Experimental results including photographs of falling drops have been presented by Magono (1954) that show that freely falling drops as small as 2.4 mm in radius are distorted. The lower side of the drop becomes flattened while the upper side is almost spherical. For smaller drops, the shape is almost spherical; Magono finds that for these smaller drops the experimental results agree quite well with existing theories. In a rather lengthy paper, McDonald (1954) discusses the influence of five factors (surface tension, hydrostatic pressure, external aerodynamic pressure, electrostatic charge, and internal circulation) on drop shape and concludes that the only insignificant factor is internal circulation.

The shapes of a large number of raindrops were measured by Jones (1959) and the data were statistically analyzed. The largest number were oblate (in the direction of fall), but a significant number were prolate. Attempts to calculate the actual distortion of a falling drop were made by Savic (1953), who used a Fourier series in cos $(n\theta)$ rather than the usual expansion in Legendre polynomials, $P_n(\cos\theta)$ for the surface of the drop. Unfortunately, no direct comparison with experiment was made. A thorough investigation, both theoretical and experimental, on the terminal velocity of drops has been made by Beard (1976) and contains an extensive number of references to early work. Accelerated motion of water drops has been studied by Sartor and Abbot (1975); they claim that for small Reynolds number ($R < 5$) their theory and experiment agree to within 10 percent.

An interesting paper by Komabayasi, Gonda, and Isono (1964) reports the lifetime of water drops before breaking. They found that for drops 5.5 mm in radius the average lifetime was 273 s, and that the lifetime decreased rapidly as the diameter of the drops increased. Also, they found that the number of drops produced by breaking a drop increased with the diameter of the drop. LeClair et al (1972) did a theoretical and experimental study of the effects of circulation on falling water drops. They present their results in extensive tables and figures. Pruppacher and Beard (1970) studied the shape of water drops at terminal velocity and found that for drops of radius less than 140 μm no distortion occurred, for radii between 140 and 500 μm the drops were slightly deformed into oblate spheroids, and for larger drops deformation occurred but the nature of the distortion is not specified. Also, an extensive list of references is given at the end of the paper. Pruppacher and Pitter (1971) investigated the shape of water drops at terminal velocity and found essentially the same result for smaller drops as was found by Pruppacher and Beard (1970). However, for large drops in the range from 500 to 2000 μm the drops formed a flat base; for larger drops, greater than 2000 μm, the drops developed a concave depression in the base.

Most of the papers investigated consider either spherical or spheroidal shapes for liquid drops moving through air. A notable exception is the paper by Taylor and Acrivos (1964), where no assumption is made as to the geometrical form the surface must conform to. They show that at a low Reynolds number ($R_e = Ua/\nu$, where U = velocity, a = radius of undistorted drop, and ν = viscosity) the drop distorts into an oblate spheroid, but at higher Reynolds number the drop distorts into a figure resembling a spherical cap.

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5. DROP EVAPORATION

5.1 Overview

Initially we did not intend to collect information on this particular topic. After we collected a number of papers, however, it was obvious that we had to make this a separate category. Nevertheless, no attempt has been made to make the search complete. The references given should be taken as more or less representative of work on drop evaporation. The effects of an acoustic wave on the vaporization of a droplet has been studied by Wieber and Mickelsen (1960). The vaporization rate was found to increase both with the amplitude and with the frequency of the acoustic signal. The report by Dellicolli and Shaffer (1973) covers much more than drop evaporation: data on charge, surface tension, and other physical constants of many compounds are given. The vaporization of a fog or mist by the action of an electromagnetic wave is considered by Svetogorov (1973); this paper gives references to the earlier Russian work. A similar analysis specifically for a 10.6-μm laser pulse is given by Glickler (1971).

The remaining papers are more or less applicable to drop evaporation but a more complete search of the literature is necessary before their significance can be evaluated.

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6. ELECTROMAGNETIC SCATTERING FROM OSCILLATING DROPS

6.1 Overview

We considered this an important topic and were very disappointed that we were able only to find four papers directly bearing on this subject. The paper by Marshall and Hitschfeld (1953) is very general and does not deal directly with the scattering from oscillating drops. The probabilistic approach is used in this paper, and considerable effort would be necessary to apply their techniques to oscillating drops. A later paper is promised by the authors, but we were unable to find it. The paper by Brook and Lantham (1968) is directly applied to the issue of oscillations of drops; they relate the oscillating frequencies of radar echos to the frequencies of characteristic drop sizes. The conclusion to their paper gives many applications of their technique to various types of particles such as snow, hail, and water drops immediately after a lightning strike.

The paper by Musgrove and Brook (1975) examines experimentally the scatter from rather large single drops (0.30 to 0.52 cm). The results of radar echos from drops are analyzed to determine the frequencies of the drops along with a measurement of the amplitude (in decibels) of the oscillation modulation. In their conclusion, the extension of their results to clouds and fogs is critically examined. Musgrove's thesis (1972) is quite lengthy and discusses in greater detail many of the intricate details of the experiments reported by Musgrove and Brook (1975). If interest is shown in this topic, more library work can be done, but we expect that the best approach may be to contact the authors of the above papers directly.

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7. ELECTROMAGNETIC SCATTERING FROM PARTICLES AND DROPS

7.1 Overview

The amount of literature on this topic is absolutely overwhelming. We therefore made no attempt to do anything near a complete literature search on this topic. Among the standard references are Kerker (1969) and van de Hulst (1957); a copy of the table of contents for these two books has been included in the compilation of papers. Both of these references contain an extensive historical reference section to the earlier work on scattering of electromagnetic radiation. To avoid repeating these earlier references, we restricted our search to more recent topics currently being investigated.

One of the more active research groups in the field of scattering of electromagnetic waves is that of Barber and coworkers (1975, 1978). The earlier paper deals with the current topic of scattering by irregular dielectric bodies. Scattering of resonant electromagnetic radiation from irregular cylinders has been investigated by Barber et al (1982) and has been shown to be useful in characterizing optical fibers. The field of computation of scattering of electromagnetic radiation has been opened up to many more research workers by the paper of Barber et al (1981), where they have coded the electromagnetic scattering problem for a microcomputer. Further work on the determination of the diameter of optical fibers is presented in the paper by Owen et al (1981). Surface plasmon fluorescence in optical fibers has been observed and analyzed by Owen et al (1981); the enhancement of the fluorescence has been attributed to the presence of coincidences with the natural mode resonance of the fibers. Messinger et al (1981) have reported giant enhancement of the inelastic scattering of electromagnetic waves caused by thin films on the surface of noble-metal spheres or by surface roughness on small spheres of noble metals.

Further work on randomly oriented irregular particles has been done by Chylek et al (1976), in which it is shown that surface waves for irregular particles, as opposed to spheres, play a much reduced role in scattering. Scattering of electromagnetic waves from absorbing spheres has been investigated by Kattawar and Plas (1967), with emphasis on efficiency of calculation of Mie cross sections. Lidar methods have been employed by Iwasaka and Isono (1977) to determine the size distribution of stratospheric aerosols at various altitudes.

A measurement technique for the size and concentration of aerosol droplets has been reported by Carlon et al (1976); this paper is a contribution to what is now a popular technique referred to as "remote sensing." Transmission of electromagnetic radiation through fogs and mists has been investigated by Chu (1968, 1967) and by Glickler (1971). Much of the Russian work done on atmospheric transmission of ele tromagnetic waves through the atmosphere is reported by Zuev (1974); the table of contents has been included. Later Russian work is reported by Bisyarin and Sokolov (1974) and Zrazhevskiy et al (1974).

Oguchi (1973) in a very detailed paper discusses the scattering properties of oblate raindrops, and Stephens and Gerhardt (1961) have calculated the absorption cross section for spherical raindrops of various sizes and a number of different wavelengths. Sinclair and La Mer (1949) report using light scattering as a tool for measuring aerosol particle size. Coherent anti-Stokes Raman scattering (CARS) has been calculated by Cooney and Green (1982) for $0.5 < \alpha < 20$ ($\alpha = 2\pi a/\lambda$, where a is the radius of a spherical drop and λ is the wavelength of the incident pump light). We expect that this paper will stimulate some experimental work in this new and fascinating area.

An excellent report by Mooradian et al (1976) covering the transmission of blue-green radiation through clouds covers a large number of factors that must be considered in such a problem. The unlikely problem they address as their ultimate goal is the transmission of blue-green light through a portion of sea water, then through clouds. A rigorous treatment of scattering in a dense medium is given by Patterson (1975), the results of which should serve as a check on any approximate theory.

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8. SIZE DISTRIBUTION

8.1 Overview

This topic was not intentionally searched, but the articles came up as a consequence of searches on other topics. Further work can be done if there is an interest. We know that there exists a large amount of literature concerning the size distribution of particles, but we have avoided attempting to make the study complete because we assumed, perhaps wrongly, that the topic was peripheral.

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9. CLOUDS

9.1 Overview

This is another topic which was not intentionally searched, but a number of rather fascinating papers were found; thus, we decided that a separate category should be given to clouds. References to earlier application of the theory of drops are included (although copies of papers were not compiled) in case there is some historical interest. The papers that are included are those that were found unintentionally and bear some relation to the main topics being searched. The subject of clouds is very fascinating not only for its technical aspects, but also because cloud formations are interesting in themselves on an everyday level. Therefore, we have included several recent papers which should provide a start in the direction of a directed bibliography project.

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10. ELECTROMAGNETIC AND ACOUSTIC EMISSION OF RADIATION FROM DROPS

10.1 Overview

This topic came as something of a surprise. That almost everything emits and absorbs radiation is common knowledge; nevertheless, the idea of a drop emitting microwave radiation had not occurred to us. Most of the papers are fairly recent (1970 to 1975), which seems to indicate that we were not alone in our ignorance. We attempted to find more references to electromagnetic radiation from drops and were unsuccessful in a simple direct search; more references may be found if a more sophisticated search is done. If there is an interest it would be a simple, but tedious, task to search out other references to this topic. One of the papers, Mackay (1982), deals with infrared emission; two papers, Sower (1980) and Keeney (1970), deal with microwave emission; and one paper, Shifrin and Chernyak (1974), deals with thermal radiation. The remainder, Bhartendu (1971) and Holmes et al (1971), deal with the power spectrum of thunder.

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11. SCAVENGING AND PRECIPITATION

11.1 Overview

Again as with some previous topics, this category came about by accident, and a sufficient number of papers were collected to force a separation from the main topic. No searches were made on the scavenging or precipitation topics, but we feel certain that if a search were made a large number of papers would be found. The paper by Hampl et al (1971) contains an extensive bibliography on scavenging, as does the report by Podzimek (1978) cited in section 12.

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12. DISPERSION OF FOG OR MIST

12.1 Overview

The emphasis of our literature search was not directed toward the dispersion of fog or mist; despite this, a sufficient number of papers appeared to make a separate category essential. It is curious that the majority of papers that cropped up in this manner were Russian; we have no assurance that a concerted search of this topic would show that the Russians are vigorously pursuing this topic. Most of the papers listed here were published in the last decade. An extensive survey of the literature in this field was conducted by Podzimek (1978).

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13. MISCELLANEOUS

13.1 Overview

Many of the papers found in this literature search did not occur with a large enough number in a particular topic to warrant the creation of a separate file for that topic. Consequently, we placed this entire group under the heading "Miscellaneous." This does not mean that the papers themselves are not worth the reading; on the contrary, some are very good and extremely interesting but they just did not fit. Many of the topics covered in this section could be further investigated if the need arises.

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