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A LIGHT-SCATTERING DIAGRAM

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ABSTRACT

A diagram is presented which shows the light scattering effectiveness of small particles when they are suspended in water. The effective scattering is plotted as a function of the radius of the particles (0.005 to 5 µ), of the wavelength of the energy being scattered (0.35 to 0.8 µ), and of the relative refractive index of the material in the particle when compared to water (1.02 to 1.40). The diagram covers the range of variables for most fine materials which are found suspended in natural waters.

INTRODUCTION

It is of interest to oceanographers and limnologists to be able to estimate the effectiveness of various types and sizes of naturally suspended materials in the scattering of solar energy in water. Such estimates may be used in the study of the light budget for photosynthesis, in underwater visibility studies, and when working with actions of phototropic organisms. Furthermore, relative scattering and related extinction have been used to characterize and trace water masses (Jerlov, 1953; Joseph, 1953) and to determine something about the size range and concentration of suspended materials (Burt, 1954, 1955a, 1955b).

The literature on theoretical results and practical applications of light scattering is found in publications in many fields. Often information is presented in a form which is applicable to a single problem and which may cover such a narrow range of variables that it is of use to that problem alone. In other cases, information is presented in forms which are difficult or impossible to assimilate without extensive training in mathematics and physics.

This note has been written in order to make available to aquatic researchers a reference diagram which will show at a glance some of the effects of the various independent variables on light scattering. More detailed and exact information, if desired, can be obtained for certain conditions from the references (Gumprechtt and Sliepcevich, 1951: 3–8; Van de Hulst, 1946; Sinclair and LaMer, 1949).

This work has been supported by Office of Naval Research, Contract Nonr 1286(02) Project NR 083–102, and Oregon State College.
SCATTERING DIAGRAM

The relative ability of particles to scatter light is usually given in terms of their effective area scattering coefficient, $K_a$, or their efficiency factor. It is defined as the dimensionless number by which the geometric cross-sectional area of a particle (in the plane perpendicular to the direction in which the original direct light beam, or pencil, is traveling) must be multiplied in order to determine its effectiveness in deflecting light from a direct beam by processes of scattering. Thus, $K_a$ is a nondimensional number equal to the energy scattered from the incident beam divided by the energy of the pencil that is geometrically obstructed by the particle. Lines of constant $K_a$, plotted in the upper part of Fig. 1, range in numerical value from $10^{-7}$ to 3.75.

The ordinate in the upper part of Fig. 1 is the relative refractive index of the material in the particles. It is found by dividing the refractive index of the material in air (as published in reference tables) by 1.33, the average refractive index of water. The range of the relative refractive indices of some of the particulate matter found in natural waters is shown on the right ordinate (Clay minerals from Grim, 1939; Bacteria and the range of other inorganic materials from Bennett, et al., 1951: 320, table V. 1).

The abscissa in the lower part of Fig. 1 is the radius of the particles in microns. The numerical value of the radius for any position on the abscissa is a function of the wave length of the energy being scattered. Thus, monocromatic light is scattered at different rates depending upon what part of the spectrum it comes from. For example, the position on the abscissa corresponding to particles with radii of 1µ for energy in the infra-red at a wave length of 0.8µ is the same as the position for particles with radii of only 0.45µ for energy in the ultra-violet at a wave length of 0.35µ. Each part of the solar spectrum must be considered separately due to the wave length effect.

The effective area coefficient is obtained from the diagram by entering with the wave length in the left-hand side of the lower diagram or with the color of light in the right-hand side, crossing horizontally to the proper radius and then moving vertically to the relative refractive index of the material in the upper diagram. The effective area coefficient is then read or interpolated for this position on the graph. For example, bacteria with a relative refractive index of 1.10 and a radius of 1µ would have an effective area coefficient ranging from 3.4 for blue light down to 2.4 for red light. The range in effective area coefficient values for fine clay with a radius of 0.1µ would
Figure 1
be $10^{-2}$ to 0.4 depending on the relative refractive index of the clay and the wave length of the light being scattered.

Note that the effectiveness of particles as scatterers for radii up to about 0.5µ increases directly with the size of the particle and the relative refractive index of the material and inversely as the wave length of the light being scattered. For particles above approximately 0.5µ, the scattering may vary directly or inversely with size, wave length, or relative refractive index, depending upon the position on the diagram. For particles with radii above 5µ, variations in numerical value of the effective area coefficient become less and less with a tendency toward a constant value of 2.0.

The direction of scattering is isotropic for very small particles (left-hand side of diagram). As the particle increases in size, scattering becomes directional. One pronounced effect of the directionality is that a sizable proportion of scattered energy tends to travel in a nearly forward direction. For the larger particles (right-hand side of the diagram), as much as 40% of the scattered energy is concentrated within a cone of only 7° in half angle centered about the direction in which the original light beam was traveling (Gumprecht and Sliepcevich, 1952: table 1).

**SOURCES**

Scattering by particles much smaller than the wave length of light was computed from Rayleigh's Law (Van de Hulst, 1946: 17). Scattering in the size range of light waves for material with relative refractive indices of 1.20 and greater was interpolated from plots in the tables of Gumprecht and Sliepcevich (1951: 3–6). Van de Hulst's equation (1946: 53) was used to compute scattering for particles with relative refractive indices near unity. Intermediate values were interpolated.

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*To obtain a maximum amount of use from the Mie theory it would be highly desirable to have information on that portion of the light which is scattered in a backward direction only. However, the preparation and presentation in graphical form of such information is not possible without considerable additional study for the range of variables shown in the diagram herewith. An effort to prepare such a diagram or set of diagrams is planned for the future.*
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