Light Scattering and Size Distribution of Particles in the Surface Waters of the North Pacific Ocean*

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Abstract: The volume scattering function and size distribution of suspended particles in the surface water were determined in the North Pacific. The relationship between the scattering coefficient estimated from observed volume scattering function and cross-section concentration of the particles greater than 2.4 μm in diameter was found to be linear in both northern and southern regions of central North Pacific. Difference in the constant of proportionality between two regions, however, was very great. Moreover the constant in the southern region was too large compared with the values obtained by the Mie theory. This is considered to be due to the fact that particles smaller than 2.4 μm which were not measureable by the Coulter Counter, were neglected in the calculation of cross-section concentration. If small particles are taken into consideration, total cross-section concentration and scattering coefficient in the two regions tend to follow a linear relation. From the correlation between the scattering coefficient computed from size distribution and the volume scattering function, the refractive index of particles was estimated to be 1.03-1.05. By the same procedure, the refractive index of particles in Tateyama Harbour where the water was very turbid, was estimated to be also 1.03-1.05. This is in contrast to the result for the refractive index of particles originating from the river which flows into the harbour. This index was found to be 1.10-1.20.

1. Introduction

The light scattering of sea water is mainly determined by the size and quality of suspended particle in it. Applying the Mie theory to a single non-absorbing spherical particle, BURT (1956) computed the efficiency factor that is closely related to the scattering coefficient as a function of size, wavelength and relative refractive index of the particle. On the other hand, JERLOV and KULLENBERG (1953) and HODKINSON (1963) experimentally determined the efficiency factor for various suspensions. The monodispersed system has usually been assumed when the observed volume scattering function is compared with a theoretical one, but some workers have assumed a polydispersed system (SASAKI et al., 1968; KULLENBERG, 1970; KULLENBERG and OLSEN, 1972; GORDON and BROWN, 1972). Since the suspended particles in natural sea water have a wide range in size, application of the polydispersed system is more realistic.

BEARDSLEY et al. (1970) measured the light scatterance at 45° and the total scattering coefficient as well as the size distribution of particles of natural suspensions in the eastern equatorial Pacific. Both the light scatterance at 45° and the total scattering coefficient were linearly related to total cross-section concentration that was computed from the observed distribution of particle size for particle above 1 μm. Thus, the general feature of the relationship between optical and particle properties was obtained. However, considering the wide variety in size and nature of the suspended particles, it should be considered that the correlation between optical and particle properties is not yet made sufficiently clear.

In order to obtain relationship between optical and particle properties in various regions of the sea, the volume scattering function and the size distribution of particles for sampled surface waters were observed on board during KH-74-2 cruise of the R. V. Hakuho Maru, from May to June, 1974, in the North Pacific. The locations of the stations where the surface waters were sampled, are given in Fig. 1.
In this paper, we present the results obtained only at the stations located in the area between 22°-44°N and 157°-165°W in the North Pacific together with in Tateyama Harbour.

2. Measurement

The scatterance meter used in the present measurement is similar to the Brice-Phoenix light scattering photometer. The angular range covered is from 25° to 140°. The scatterance of the sampled water at the wavelengths 436 nm, 546 nm and 578 nm were measured at intervals of 5° and 10° in the angular ranges from 25° to 60° and from 60° to 140°, respectively. The signals from the meter were usually recorded for several successive seconds at each angle and the average values were taken. The meter was absolutely calibrated in advance with the value for pure benzen of which scatterance at 90° was reported by Cantow (1956).

The size distribution of particles was determined by the Coulter Counter of Type ZB with 100 μm aperture which is able to count particles of size range between 2.4 μm and 40 μm. The measurement was made four times for a sample and the average value was adopted.

The surface water was taken up with a polyethylene bucket from the deck. The measurement of both scatterance and size distribution was made in most cases within 12 hours after sampling.

3. Relation between scatterance and cross-section concentration

According to the Mie theory, the particle scattering coefficient \( b_p \) for polydispersed system is given by

\[
b_p = \frac{1}{4} \pi \sum Q_i N_i D_i^2
\]

where \( Q_i \) is the efficiency factor, \( N_i \) the number of particles of diameter \( D_i \) per unit volume. As shown in Fig. 2, \( Q_i \) approaches to 2 with increasing size. In this case, (1) is reduced to

\[
b_p = \frac{1}{2} \pi \sum N_i D_i^2
\]

The total cross-section concentration \( \Sigma S \), is defined by

\[
\Sigma S = \frac{1}{4} \pi \sum N_i D_i^2
\]

Accordingly, substitution of (3) in (2) gives

\[
b_p = 2 \Sigma S
\]

Thus, the scattering coefficient for large particles is directly proportional to the total cross-section
Fig. 2. The variation of efficiency factor with the refractive index as a function of size parameter.

concentration. Since the number of particles greater than 2.4 μm and less than 40 μm in diameter was measured, the cross-section concentration of particles in this range of size can be evaluated by means of (3). On the other hand, scattering coefficient $b_p$ is estimated from the observed volume scattering function as follows: as the first step, the partial particle scattering coefficient $b_p^*$ in angular range between 25° and 140° is calculated from volume scattering function $\beta(\theta)$ by subtracting the theoretical value for pure sea water ($\beta_0$) which was reported by MOREL (1974). Thus,

$$b_p^* = 2\pi \int_{25}^{140} \beta(\theta) \sin \theta d\theta - 2\pi \int_{25}^{140} \beta_0(\theta) \sin \theta d\theta$$

(5)

In the numerical integration of (5), the scattering angle increments adopted were 5° and 10° in the range from 25° to 60° and from 70° to 140°, respectively. Using the value of $b_p^*$ calculated, $b_p$ was then estimated in the following way.

From the angular distribution of volume scattering function observed by several workers in various areas, JERLOV (1976) concluded that the forward scattering functions show a similarity in shape. If this is actually the case, it would be quite reasonable to assume that $b_p$ and $b_p^*$ is linearly related. On this assumption, the estimation of ratio $b_p/b_p^*$ is made by using the values of volume scattering function observed at various regions by PETZOLD (1972) as well as those of pure sea water reported by MOREL (1974). In most cases the ratio is in the range from 5 to 6.5 with the average value of 5.7. On the other hand, JERLOV (1953) also suggested that scattering coefficient $b$ can be represented by $\beta(45°)$. In the present work, the relation between $\beta(45°)$ and $b$ calculated from $b_p^*$ on the assumption that $b_p/b_p^*$ is 5.7, is shown in

Fig. 3. Relation between scatterance at 45° and scattering coefficient estimated from partial scattering coefficient at the wavelength of 546 nm in the North Pacific.
Fig. 3. The ratio $\beta(45^\circ)/b$ is 0.028 in this case and this compares well with the data which were obtained by several workers and summarized by Jerlov (1976). In the meanwhile, Mankovsky and Neuymin (1975) showed the relation which exists between $b$ and $\beta(\theta)$ as a function of $\theta$. According to their results the correlation coefficient between them is small at very small angles but increases rapidly with increasing $\theta$ and attains a peak of 0.96 at about $4^\circ$. From $4^\circ$ towards large angles the coefficient gradually decreases with a few small scale oscillations but still keeps almost the same level of 0.7 even in the backward direction. Judging from their results, the correlation coefficient between $b_p$ and $b_p^*$ in the present work should be considerably larger than 0.7 because a significant fraction of $b_p^*$ comes from $\beta(\theta)$ at angles near $25^\circ$ where the correlation coefficient is nearly 0.85.

Fig. 4 shows the relation between the cross-section concentration $\Sigma S$ and the particle scattering coefficient $b_p$ estimated from $b_p^*$ at the wavelength of 546 nm. At a glance the correlation between $b_p$ and $\Sigma S$ is not good. However, if we classify the data into two groups according to the region in which the data were obtained, some correlation between $b_p$ and $\Sigma S$ is observed. The calculated correlation coefficient for the data taken in the northern region of the central North Pacific (Stns. 1–9) was 0.74 and that for those taken in the southern region (Stns. 10–22) was 0.86. It is, moreover, noticeable that the difference in the slope of the correlation lines between the two areas is significantly great.

Beardsley et al. (1970) observed the light scattering and size distribution of particles in the eastern equatorial Pacific and pointed out that the particle scatterance and cross-section concentration of particles larger than 1 $\mu$m is linearly related. Judging from the results obtained here, the linear relation between scatterance and cross-section concentration of particle larger than 2.4 $\mu$m is valid only for narrow areas where the particles are expected to have a similar quality and size distribution.

The straight lines in Fig. 4 indicate the relation between $\Sigma S$ and $b_p$ when they are proportional to each other, efficiency factor being taken as parameter. Therefore, the constants mean the average values of efficiency factor ($\overline{Q}$) as clearly seen in (1) and (3). The set of points for the northern region fits the straight line for which $\overline{Q} (= b_p/\Sigma S)$ is equal to about 2. On the other hand, the points for the southern region fit the line when $\overline{Q}$ is about 5. It is evident, from Fig. 2, that $Q$ value is nearly 2 when the particle size is large and fluctuates between certain values as the particle size becomes smaller but can not take a value larger than 3.7 if the refractive index is less than 1.20. The $\overline{Q}$ values obtained in the northern region lie, therefore, in the reasonable range of values but those obtained in the southern region are too large. This is considered to be due to the fact that we neglected the contribution of particles smaller than 2.4 $\mu$m in the calculation of $\Sigma S$.

Beardsley et al. (1970) pointed out that small particles have significant effect on the scatterance judging from the existence of X-intercept of line which shows the relation between $\beta(45^\circ)$ and cross-section concentration above 1 $\mu$m.

In the present case, the distribution of particle size for particles smaller than 2.4 $\mu$m is not known. The average cumulative size distributions in the northern and southern regions for particles larger than 2.4 $\mu$m are presented in Fig. 5. Particles between 2.4 $\mu$m and 6.1 $\mu$m were more abundant in the northern region than in the southern region. Judging from the
size distribution near 2.4 \( \mu \)m, however, the number of particles smaller than 2.4 \( \mu \)m in the southern region is supposed to be more than that in the northern region. Observed size distribution between 2.4 \( \mu \)m and 6.1 \( \mu \)m is approximately hyperbolic in shape. Accordingly, a hyperbolic distribution is also assumed for the particles smaller than 2.4 \( \mu \)m in the calculation. The cumulative particle size distribution is then given by

\[
N_{>n}(D) = AD^{-\xi} \quad (D<2.4 \mu) \quad (6)
\]

where \( N_{>n}(D) \) is the number of particles larger than diameter \( D \) and \( A \) and exponent \( \xi \) are parameters to be determined from the observed size distribution above 2.4 \( \mu \)m. From the extrapolated distribution thus obtained, the total cross-section concentration is computed by (3). The computation is carried out down to 1.0 \( \mu \)m and the contribution from particles smaller than that was neglected. The increment of size parameter \( \Delta \alpha = \frac{\pi}{\lambda} AD \), in this case, was 0.2. The relation between computed cross-section concentration and the scattering coefficient at the wavelength of 546 nm is shown in Fig. 6. The total cross-section concentration in the northern region increases in some degree when the contribution of small particles is taken into consideration: most of the points are located between the two lines having the slopes of 0.5 and 1.5. On the other hand, in the southern region the total cross-section concentration increases considerably with the contribution of small particles, all the points being located above the straight line of slope 2.0. Judging from the behaviour of \( Q \) as shown in Fig. 2, it is plausible that \( \bar{Q} \) is less than 2. Thus if we take the contribution of small particles into consideration, the total cross-section concentration and the scattering coefficient in both regions tend to follow a linear relation although the scattering of points is striking. The scattering of points is attributed to the over- or under-estimation in the number of small particles and also the difference in the refractive index of particles as described in the following section.

4. Estimation of refractive index of particles

As shown in Fig. 2, the effect of refractive
index of particles on scatterance is considerable. This implies the possibility of estimating the refractive index of particles from optical and particle size measurements.

Morel (1973) evaluated the refractive index of particles on the basis of the ratio of volume scattering functions at two selected angles as well as the size distribution. Zaneveld and Pak (1973) and Brown and Gordon (1973) also presented methods for determining the refractive index from the observed data on \( \beta(45^\circ) \) and size distribution of particles. In the present work, the refractive indices of particles in northern and southern North Pacific are

Fig. 7. Relation of particle scattering coefficients estimated from size distribution to those estimated from partial scattering coefficient in the central North Pacific.
estimated as follows:

The particle scattering coefficient can be calculated from the size distribution of particles by Eq. (1). The particle scattering coefficients computed from the size distribution in two regions are plotted against those estimated from \( b_p \), in Fig. 7. In this case, the particles of non-absorbing spheres of which refractive indices are 1.03 and 1.05, are assumed in the computation. Points are scattered over a wide area. When the refractive index is taken to be 1.03, most points obtained for the northern region are located in the vicinity of a straight line, which indicates a one-to-one correspondence between two estimated coefficients. Most points obtained for the southern region, however, are found below this line. On the other hand, when the refractive index is taken to be 1.05 the fit to the line showing one-to-one correspondence is found in the southern region but not in the northern region. Therefore, the assumption that the size distribution of particles whose diameter lie between 1.0 \( \mu \)m and 2.4 \( \mu \)m obeys the power law leads to the conclusion that the refractive indices of particles are about 1.03 in the northern region and 1.05 in the southern region of central North Pacific. The results obtained here are not so accurate because the correlation between two estimated coefficients is not so good and also both coefficients were estimated under a few assumptions. It is, however, reasonable to accept that the refractive index of particles in the central North Pacific lies between 1.03-1.05. The result coincide with the values of 1.05-0.01\( \iota \) obtained by GORDON and BROWN (1972) in the Sargasso Sea and of 1.02-1.05 by MOREL (1973) in various areas. On the other hand, PAVLOV and GRECHUSHNIKOV (1966) estimated the refractive index of minerals in the sea to be 1.17, a value higher than that of organic matter.

In the present observation, the waters including an abundance of whitish particles were sampled at the harbour of Tateyama (Stn. S-43). This water zonally extended from the river mouth and showed great difference in colour from the surrounding water which looked yellow. These whitish particles are considered to be composed of inorganic matters. On the other hand, the water sampled from the sur-}

![Fig. 8. Relation of particle scattering coefficients estimated from size distribution to those estimated from partial scattering coefficient at Stns. S-42 and S-43.](image-url)
the refractive index of particles are not so accurate since the present computation were carried out under several assumptions. Particularly, the assumption of the linear relation between $b_p$ and $b_p^*$ and that of hyperbolic distribution for the small particles are supposed not necessarily to be valid in all cases. Nevertheless, it is suggested that the contribution from small particles should be taken into consideration in order to obtain the relationship between optical and particle properties. In spite of the significant role in light scattering of the small particles, few data are available on the size distribution of small particles and more detailed investigation in this field is greatly required.

Acknowledgements
The authors would like to thank Mr. N. OKAMI, Inst. Phys. Chem. Res., for his valuable discussion and suggestions. To Mr. M. KISHINO, Inst. Phys. Chem. Res., the authors are much indebted for providing the programs of the Mie theory and also for his kind advices and criticism.

To Dr. K. KIDO, JANUS, Co., who gave us technical suggestion and advice on operating the Coulter Counter, the authors feel grateful.

Kind help and encouragement during the expedition given by Prof. T. KUROKI, Tokyo University of Fisheries, members of KH-74-2 expedition and the crew of the R. V. Hakuhu Maru, Ocean Research Institute, University of Tokyo, are gratefully acknowledged.

The authors are indebted to Dr. M. SHIMA, Inst. Phys. Chem. Res., for his kind advice and encouragement.

References
海中懸濁物の粒径分布と光散乱について

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要旨: 白鳥丸北太平洋航海(KH-74-2)において表面水を
採取し海中懸濁物の粒径分布と光散乱関数を測定した。解
割効果より求めた散乱係数と粒径分布より求めた散乱
断面積との相関を考慮して見ると良くないが太平洋
中央部の北と南の個々の海域は良い。この相関関
係より推定される散乱効率は Mie の理論により予想さ
れる値に比べ南部の海域では高過ぎる。これは粒径分布
から散乱断面積を求めるとき 2.4μm 以下の小粒子の寄
与を無視した為と考えられる。この小粒子の粒径分布は
べき乗分布で表わされると仮定し小粒子を含む散乱断面積
を計算した。小粒子の寄与を考慮した散乱断面積と散乱
係数の相関関係はこの仮定の正しい事を示す。粒径分布
と散乱関数より求めた二つの散乱係数の相関を調べる事
により太平洋中央部の海中懸濁物相対屈折率は 1.03
から 1.05 附近にあると推定出来た。また同様方法によ
り鶴山港の流された海水中の懸濁物屈折率は 1.03-1.05 で
あり河川から流入した自流性の懸濁物屈折率は 1.10-1.20 と推定出来た。

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