Light scattering by pure water and seawater: the depolarization ratio and its variation with salinity

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We measured the linearly polarized light scattering of pure water and seawater at various salinities and estimated the depolarization ratio using five different methods of data analysis after removing the scattering due to contamination by residual nanoparticles. The depolarization ratio values (δ) estimated for pure water using these different methods are largely consistent with each other and result in a mean value of 0.039 ± 0.001. For seawater, our results reveal a trend of a slight linear increase of δ with salinity (S), δ = 0.039 + a1 × S, where a1 varies in the range of 1 × 10⁻⁴ to 2 × 10⁻³ between the methods.

1. INTRODUCTION

It is well recognized that one key challenge in further improving our understanding of light scattering by seawater is better knowledge of the depolarization ratio of pure water and its variation with salinity [1]. Due to anisotropic molecular structure, the scattering at 90° by water is not completely polarized as expected for an isotropic molecule [2]. As a fundamental physical property, the depolarization ratio is defined as a ratio of horizontally to vertically polarized light scattered at 90° when the incident light is unpolarized. Depolarization also increases the magnitude of scattering, an effect called the Cabannes factor [3]. The current uncertainty in the values of the depolarization ratio of pure water is at least ±50%, whereas the uncertainties of the other fundamental physical parameters used to compute the scattering by water are <0.1% [1].

Interests in better quantifying the scattering by pure water (and other pure liquids) led to considerable efforts in measuring the depolarization ratio of water, mostly before the 1970s. The most recent measurement was conducted by Farinato and Rowell [4]. Kratohvil et al. [5] compiled then-up-to-date results, which we extend in Table 1 to include later studies on measuring the depolarization ratio of pure water. Examining Table 1, one can notice several differences in the measurements conducted before and after 1970. First, either polychromatic light or emission at Hg wavelengths of 436 and 546 nm were used before 1970, whereas lasers were used after 1970. Also, the observations before 1970 tend to have higher values and exhibit larger variations among different experiments. Pike et al. [25] commented that technological advancements, particularly the use of lasers, had allowed a better measurement of the depolarization ratio. Farinato and Rowell [4] further argued that in addition to the use of lasers, elimination of stray light contamination was critical because the horizontal component of the scattered light at 90° by water is so small that a slight contamination by stray light would cause an overestimation of the depolarization ratio. In their experiment, Farinato and Rowell [4] were able to derive gradually decreasing depolarization ratio values by progressively reducing the stray light.

Among the values of the depolarization ratio listed in Table 1, several have been recommended for use to calculate scattering by pure water. Kratohvil et al. [5] suggested a value of 0.108, which was the mean of their measurements at the two wavelengths of 436 and 546 nm. Morel [26] and Shifrin [27] used a value of 0.091 measured by Pethica and Smart [21] at 436 nm. Buiteveld et al. [28] used a value of 0.051 measured by Farinato and Rowell [4] at 514.4 nm. Jonasz and Fournier [29] recommended a value of 0.039, also measured by Farinato and Rowell [4] but after removal of stray light using a filter with a half power band width of only 0.46 nm. Using the latest thermodynamic data of water and improved estimates of the density derivative of the refractive index of water [30–32], Zhang and Hu [33] were able to model the scattering by pure water that agrees with the Morel [26,34] measurements within 2% using either value of 0.051 or 0.039, but a better agreement was obtained when the value of 0.039 was used. Recently, the ocean optics community seems to have converged on recommending using 0.039 as the depolarization ratio for pure water [1]. The current value of 0.039 was determined by Farinato and Rowell [4] for pure water more than 40 years ago, and to the best of our
knowledge there has been no additional verification of their measurement. This leads to the first motivation of our study.

The linearly polarized scattering of bulk oceanic and coastal waters has been measured [35–38]. From these measurements, which are often provided as the degree of linear polarization ($\delta$) as a function of scattering angle, we estimated the depolarization ratios, calculated as $[1 - p(90)]/[1 + p(90)]$, which vary from 0.1 for clear oceanic waters to 0.43 for turbid waters. These estimates are generally greater than the pure water values listed in Table 1; however, they include not only the molecular contribution to scattered light but also the contribution by suspended particles. The natural particle assemblages in seawater tend to enhance the depolarization ratio as the particles. The natural particle assemblages in seawater tend to enhance the depolarization ratio as the scattering angle increases, but the rate or even the direction of change varies among different salt solutions. For example, his measurements showed that the depolarization ratio of a NaCl solution increases with the salt concentration, whereas that of a KCl solution decreases with the concentration. The presence of disassociated salt ions introduces two contrasting effects: the isotropic electrostatic field produced by ions decreases the depolarization ratio [21], and increased anisotropy of water molecules attracted by the ions increases the depolarization ratio [41]. It is still unknown, however, if and how the depolarization ratio of pure seawater varies with salinity. It is currently assumed that the depolarization ratio of seawater does not change with salinity [42,43].

Table 1. Measured Values of the Depolarization Ratio of Pure Water ($\delta$)

<table>
<thead>
<tr>
<th>Authors</th>
<th>$\delta$ (Wavelength)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Martin and Lehman [6]</td>
<td>0.067</td>
</tr>
<tr>
<td>Raman and Rao [7]</td>
<td>0.125, 0.094 (red), 0.106 (yellow), 0.107 (green), 0.155 (blue), 0.210 (violet)</td>
</tr>
<tr>
<td>Gans [8]</td>
<td>0.120</td>
</tr>
<tr>
<td>Krishnan [9]</td>
<td>0.079</td>
</tr>
<tr>
<td>Rocard [10], Rocard [11]</td>
<td>0.110</td>
</tr>
<tr>
<td>Martin [12]</td>
<td>0.109</td>
</tr>
<tr>
<td>Sweitzer [13]</td>
<td>0.109</td>
</tr>
<tr>
<td>Lotmar [14]</td>
<td>0.077</td>
</tr>
<tr>
<td>Peyrot [15]</td>
<td>0.088 (436 nm)</td>
</tr>
<tr>
<td>Hogrebe [16]</td>
<td>0.060</td>
</tr>
<tr>
<td>Dawson and Hulburt [17]</td>
<td>0.100</td>
</tr>
<tr>
<td>Hoover et al. [18]</td>
<td>0.077</td>
</tr>
<tr>
<td>Kraut and Dandliker [19]</td>
<td>0.083 (436 nm)</td>
</tr>
<tr>
<td>Prins and Hermans [20]</td>
<td>0.15 (436 nm)</td>
</tr>
<tr>
<td>Pethica and Smart [21]</td>
<td>0.091 (436 nm), 0.109 (546 nm)</td>
</tr>
<tr>
<td>Rao and Foster [22]</td>
<td>0.09 (546 nm)</td>
</tr>
<tr>
<td>Kratochvil et al. [5]</td>
<td>0.10 (436 nm), 0.116 (546 nm)</td>
</tr>
<tr>
<td>Cohen and Eisenberg [23]</td>
<td>0.087 (436 nm), 0.076 (546 nm)</td>
</tr>
<tr>
<td>Kaye and Havlik [24]</td>
<td>0.076 (546 nm)</td>
</tr>
<tr>
<td>Pike et al. [25]</td>
<td>0.076 (633 nm)</td>
</tr>
<tr>
<td>Farinato and Rowell [4]</td>
<td>0.051 (514.5 nm, no stray light filter), 0.045 (514.5 nm, stray light filter with a half-power band width (HPBW) of 22.5 nm), 0.039 (514.5 nm, stray light filter with a HPBW of 0.46 nm)</td>
</tr>
</tbody>
</table>

*If the light wavelength is not given, polychromatic light was used in the measurements. The dotted line separates the measurements conducted before and after 1970.

2. METHODS AND THEORY

We attempted to prepare pure seawater using commercially available evaporated sea salts rinsed with ultrapure water, but found the sample contamination by nanoparticles unacceptably high even after 20 nm filtration. This may indicate contamination of the salt crystals during the production process (outdoor evaporation ponds) or result from the spontaneous aggregation of remnant organic matter or nanoparticles in the filtrate [45].

A. Pure Water and Pure Seawater Preparation

Ultrapure water was produced using a water purification system (Simplicity UV, EMD Millipore) equipped with an ultrafiltration cartridge (BioPak polisher, EMD Millipore). The specifications of dispensed water relevant to our study are: total...
 organic carbon (TOC) ≤ 5 ppb, particulates (size > 0.2 μm) <1 mL⁻¹, and specific resistance at 25°C = 18.2 MΩ cm. We will refer to ultrapure water as pure water.

Five salt compounds of ultrahigh purity were used to prepare artificial pure seawater. These compounds were: 99.999% trace metals basis NaCl (Sigma-Aldrich), 99.995% trace metal basis KCl (Alfa Aesar), Certified ACS Grade 99–105% CaCl₂·2H₂O (Fisher Scientific), Certified ACS Grade 99–102% MgCl₂·6H₂O (Fisher Scientific), and Certified ACS Grade ≥ 99% Na₂SO₄ (Fisher Scientific). With a mass ratio of 0.5850:0.0180:0.0364:0.2636:0.0971 for NaCl:KCl:CaCl₂·2H₂O:MgCl₂·6H₂O:Na₂SO₄, which represents an anhydrous salt mass ratio of 0.6875:0.0211:0.0323:0.1451:0.1141 for NaCl:KCl:CaCl₂·2H₂O:MgCl₂·6H₂O:Na₂SO₄, the ion proportions of Cl⁻, Na⁺, SO₄²⁻, Mg²⁺, Ca²⁺, and K⁺ in solution are similar to natural seawater within <0.5%.

Mixed salts were weighed (Mettler-Toledo MT5 microbalance, 1 μg precision) and then dissolved in ultrapure water to produce a salt solution of ~200 mL. The prepared salt solution was further filtered through a 20 nm syringe filter (Anotop 25, Whatman) to produce a “master” salt solution, which was used to prepare seawater at different salinities through further dilution with ultrapure water. The salinity of a prepared seawater sample was computed using the mixing ratio. The salinity and temperature of the master salt solution, as well as each solution prepared through dilution, were also measured using a handheld conductivity meter (Model 30, YSI). The measured salinity, which is in Practical Salinity Units (PSU), was converted to mass concentration following 1 PSU = 1.0047 × S (PSU) [46]. The differences in salinity between calculated and measured values were <1.5%. Measured values of salinity and temperature were used in the data analysis. Two master salt solutions were prepared, one with a salinity of 39.68 g kg⁻¹ and the other 40.01 g kg⁻¹. Two separate experiments were conducted, one for each master salt solution. The two experiments were made with identical methodology with sample salinities having slightly different discrete values but covering a similar range in order to increase the number and resolution of sample salinities. Both experiments were carried out at room temperature, with sample temperatures varying from 23.2°C to 24.5°C and from 21.2°C to 25.2°C, respectively.

\[
M = \beta(90, \delta) \begin{pmatrix}
1 + \frac{1}{2} \delta \cos^2(\theta) & \frac{1}{2} \delta \sin^2(\theta) & 0 & 0 \\
\frac{1}{2} \delta \sin^2(\theta) & 1 + \frac{1}{2} \delta \cos^2(\theta) & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 2 \frac{1}{2} \delta \cos(\theta)
\end{pmatrix},
\]  

(1)

B. Light Scattering Measurements

Light scattering measurements of pure water and seawater solutions were obtained by placing a cylindrical glass vial containing 20 mL of sample within the enclosed chamber of a DAWN EOS multi-angle light scattering instrument (Wyatt Technologies). The instrument used in our study employs a diode-pumped frequency-doubled Nd:YAG laser to produce a beam of light at a wavelength of 532 nm and is also equipped with a liquid crystal variable retarder (LRC-100-VIS, Meadowlark Optics) to produce incident light with two linear polarization states horizontal and vertical relative to the scattering plane. During the process of setting the retarder to produce the beam with linear vertical and horizontal polarizations, we measured the contrast (or extinction) ratio of the linear polarization for both the vertical and horizontal polarization settings of the retarder under the conditions (in particular, ambient lab temperature) used in our experiments. This value, representing the ratio of the maximum to minimum light intensity of the two linearly polarized components transmitted for a given polarization setting of the retarder, was close to or higher than 700:1 and was similar (within 5%) for both polarization settings of the retarder. The 18 photodiode detectors of DAWN, each with selectable gain, have no polarization analyzer and thus provide measurement of the total scattered light intensity at 18 angles from 22.45° to 147° for each polarization state of the incident beam. This instrument is calibrated by a combination of absolute calibration at 90° by measuring light scattering by pure toluene and relative scaling at other angles by measuring the isotropic fluorescence of Rhodamine 6G dye [47]. The refractive index of each seawater sample was computed using measured temperature and salinity [48]. The use of temperature and salinity-dependent refractive index represents a slight modification in the calculation of the calibration constant for the instrument as described in Babin et al. [47].

For a given sample, 1440 measurements of angular scattering at 18 angles were acquired at a sampling frequency of 8 Hz for each incident polarization state. These measurements were then repeated for two additional random orientations of the cylindrical vial. In order to minimize the impact of residual particle contributions to scattering in the samples, for each vial orientation we processed the data by selecting and averaging the lowest 5% of scattered light intensities obtained at each angle for each incident polarization state. The minimum value of these three averages at each angle for each incident polarization state was then selected to represent the angular scattering measured for the sample.

C. Theoretical Basis

For a pure liquid or an aqueous solution, such as water or seawater, the Mueller scattering matrix M is
where \( V \) represents the scattering volume and \( r \) the distance from the scattering volume to the detector. The Stokes vector components have units of \( \text{W m}^{-2} \), and the Mueller scattering matrix components in Eq. (1) have units of \( \text{m}^{-1} \text{sr}^{-1} \). For unpolarized, linear vertically polarized (i.e., perpendicular to the measurement plane) and linear horizontally polarized (i.e., parallel to the measurement plane) incident light, the corresponding Stokes vectors \( S_v \) and \( S_h \) are \( S_v = [I_0, 0, 0, 0] \), \( S_h = [I_0, -I_0, 0, 0] \), respectively. If there is a polarization analyzer placed in front of the detector, the system Mueller matrix will be \( \mathbf{A}^{-1} \mathbf{M} \), where \( \mathbf{A} \) is the Mueller matrix for the analyzer. For a linearly polarized analyzer with a vertical or horizontal transmission, the corresponding Mueller matrices \( \mathbf{A}^v \) and \( \mathbf{A}^h \) are

\[
\mathbf{A}^v = \frac{1}{2} \begin{bmatrix}
1 & 1 & 0 & 0 \\
1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix},
\]

\[
\mathbf{A}^h = \frac{1}{2} \begin{bmatrix}
1 & -1 & 0 & 0 \\
-1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix},
\]

respectively.

With an unpolarized incident light and no analyzer in front of the detector, the measured scattered light \( I(\theta) \) is

\[
I(\theta) = \frac{V}{r^2} I_0 \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos^2 \theta \right),
\]

and, by definition, the volume scattering function \( \beta(\theta, \delta) \) is

\[
\beta(\theta, \delta) = \frac{I(\theta) r^2}{V I_0} = \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos^2 \theta \right).
\]

Note that the quantity \( I(\theta) r^2 \) in Eq. (4) is the intensity of scattered light in units of \( \text{W} \text{sr}^{-1} \), where the solid angle is derived from the ratio of receiving area of the detector to \( r^2 \). With the same setup but adding a vertical analyzer before the detector, the measured scattered light \( I^v(\theta) \) becomes

\[
I^v(\theta) = \frac{V}{r^2} I_0 \beta(90, \delta) \frac{2}{1 + \delta}.
\]

Similarly, with a horizontal analyzer, the measured scattered light \( I^h(\theta) \) becomes

\[
I^h(\theta) = \frac{V}{r^2} I_0 \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos 2\theta \right).
\]

Here the superscripts \( v \) and \( h \) indicate the polarization state of the analyzer. The ratio of \( I^h \) and \( I^v \) at 90° leads to the definition of the depolarization ratio,

\[
\delta = \frac{I^h(90)}{I^v(90)}.
\]

The DAWN instrument we used has no analyzer, but its incident light can be generated in two polarization states: linear vertical and linear horizontal. The received scattered light \( I_\beta(\theta) \) and \( I_\alpha(\theta) \), where the subscripts \( \nu \) and \( \beta \) indicate the polarization state of the incident light, are, respectively,

\[
I_\nu(\theta) = \frac{V}{r^2} I_0 \beta(90, \delta) \frac{2}{1 + \delta},
\]

and

\[
I_\beta(\theta) = \frac{V}{r^2} I_0 \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos 2\theta \right).
\]

Apparently, \( I^v \) and \( I^h \) are exactly the same; so are \( I^\nu \) and \( I^\beta \). This is expected because it reflects the reciprocity relation of light [49,50]. Combining Eqs. (8) and (9), we have

\[
\beta(\theta, \delta) = \frac{(I_\beta(\theta) + I_\nu(\theta))^2}{2 V I_0} = \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos^2 \theta \right),
\]

which is the same as Eq. (4). In addition, we define

\[
\beta_\delta(\theta, \delta) = \frac{I_\delta(\theta) r^2}{V I_0} = \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos 2\theta \right),
\]

and

\[
\beta_h(\theta, \delta) = \frac{I_h(\theta) r^2}{V I_0} = \beta(90, \delta) \left( 1 + \frac{1 - \delta}{1 + \delta} \cos 2\theta \right).
\]

With vertical and horizontal polarized incident light, the DAWN instrument measures \( \beta_v \) and \( \beta_h \), respectively, which, in turn, can be interpreted as the horizontal and vertical components of the volume scattering function. Figure 1(a) shows angular variations of \( \beta_v \) and \( \beta_h \) for different values of the depolarization ratio calculated using the Zhang and Hu [33] pure water scattering model. The value of \( \delta \) affects the magnitude of both \( \beta_v \) and \( \beta_h \) and the angular shape of \( \beta_h \). The value of \( \beta_v \) does not change with angles. From \( \beta_v \) and \( \beta_h \), the volume scattering function \( \beta \) is

\[
\beta = (\beta_h + \beta_v) / 2.
\]

Using measurements at \( \theta = 90^\circ \), we can estimate the depolarization ratio as

\[
\delta = \frac{I_h(90)}{I_v(90)} = \frac{\beta_h(90)}{\beta_v(90)}.
\]

From the measurements, we also have

\[
f(\theta, \delta) = \frac{\beta_h(\theta, \delta)}{\beta_v(\theta, \delta)} = \frac{1 + \delta + (1 - \delta) \cos 2\theta}{2},
\]

which can be used to estimate \( \delta \) using measurements at angles other than 90°,

\[
\delta = \frac{f(\theta, \delta) - \cos^2 \theta}{\sin^2 \theta}.
\]

When \( \theta = 90^\circ \), Eq. (16) reduces to Eq. (14). Figure 1(b) shows \( f(\theta) \) calculated for pure water for three different depolarization ratios of 0.03, 0.05, and 0.09.

To further illustrate how the shape of \( \beta_v \) changes with \( \delta \), ratios of \( \beta_v(\delta = 0.03, 0.05, \text{and } 0.09) \) to \( \beta_v(\delta = 0.039) \) of pure water are calculated as a function of scattering angle [Fig. 1(c)]. Comparison of the solid lines in Figs. 1(a) and 1(c) shows that the change in \( \beta_v \) shape for different values of the depolarization ratio can be better captured by forming this \( \beta_v \) ratio.
Even though the definition of the depolarization ratio is for a scattering angle of 90°, the scattering at other angles also contains information on the depolarization ratio [e.g., Eq. (15)]. To fully utilize this information and to reduce the experimental uncertainties, we use five different methods of data analysis to estimate the depolarization ratio as described in Table 2.

Because $\beta_d(90)$ for seawater is typically 3% to 5% of $\beta_s(90)$, a direct estimate using the definition of the depolarization ratio (Method 1) requires a very high sensitivity of the instrument and is subject to influence of noise due to low signal-to-noise ratio for measuring $I_h$. Using the additional methods as listed in Table 2 can partially mitigate this issue by estimating $\delta$ at multiple scattering angles statistically either through direct averaging or curve fitting. We applied Methods 2 to 5 using measurements only between 70° and 110° for two reasons. First, significant changes in the angular shape of $\beta_b$ and the ratios involving $\beta_d$ occur in this angular range [e.g., see Figs. 1(b) and 1(c)]. Second, the unwanted scattering by residual nanoparticles that potentially contaminates the samples exerts less impact on scattering in this angular range compared to smaller forward scattering angles (discussed below). The uncertainty associated with each method was estimated using propagation of errors based on measurement uncertainty for each polarization state, which will be discussed in Section 3.D.

**D. Effect of the Field of View of the Scattering Detector**

The depolarization ratio is defined mathematically at an angle of 90°, but all scattering detectors have a finite angle of acceptance. The measurement at 90° or any other nominal scattering angles includes light scattered at angles contained within a sensor’s field of view (FOV). Assuming a detector has an acceptance angle of $2\alpha$ and a response function $F(\theta)$ (where $\frac{1}{2\alpha}R_{\theta_o}F(\theta)d\theta = 1$ and $\theta_0$ is the nominal scattering angle), the measured depolarization ratio $\delta_0$, following Eq. (16), is

$$\delta_0 = \frac{\int_{\theta_o - \alpha}^{\theta_o + \alpha} R_{\theta_o}F(\theta)\sin^2\theta d\theta - \cos^2\theta_0}{\sin^2\theta_0}. \tag{17}$$

Assuming $F(\theta) = 1$ for simplicity and using $\sin\alpha \approx \alpha$, Eq. (17) can be approximated as

$$\frac{\delta_0}{\delta} \approx 1 + \cot^2\theta_0 - (\cot^2\theta_0 - 1)\cos\alpha \div \frac{2}{\delta} - (\cot^2\theta_0 - 1)(1 - \cos\alpha). \tag{18}$$

In our study, we used measurements from 70° to 110° (i.e., 70° < $\theta_0 < 110°$) to estimate $\delta$. Within this angular range, $\delta_0/\delta > 1$, the effect of the FOV of a detector leads to an overestimation of the depolarization ratio in our study. Also, this overestimation increases with the acceptance angle ($2\alpha$) and with decreasing values of $\delta$. The DAWN detectors have an acceptance angle of 2.2° ($\alpha = 1.1°$), and for the range of $\delta$ values that have been reported for pure water (0.039 to 0.11; Table 1) the overestimation is only 0.1 to 0.2%, which can

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**Table 2. Summary of Five Different Methods Used to Estimate the Depolarization Ratio ($\delta$) of Seawater and Estimates of the Associated Uncertainty**

<table>
<thead>
<tr>
<th>Method to Estimate $\delta$</th>
<th>Estimated Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Apply the definition of depolarization ratio, i.e., Eq. (14).</td>
<td>4.94</td>
</tr>
<tr>
<td>2. Use Eq. (16) to estimate the values of $\delta$ at angles between 70° and 110° and take the average of these estimates.</td>
<td>1.78</td>
</tr>
<tr>
<td>3. Use Eq. (15) to compute $f(\theta)$ from the measurements at angles between 70° and 110° and apply curve fitting to find $\delta$ such that the theoretical $f(\theta)$ [Fig. 1(b)] fits best to the measured $f(\theta)$.</td>
<td>1.78</td>
</tr>
<tr>
<td>4. Compute ratio of measured $\beta_s$ to theoretical $\beta_d$ ($\delta = 0.039$) at angles between 70° and 110° and apply curve fitting to find $\delta$ such that the theoretical ratio [Fig. 1(c)] fits best to the measured ratio.</td>
<td>1.76</td>
</tr>
<tr>
<td>5. Apply curve fitting to find $\delta$ such that the theoretical $\beta_d$ [Eq. (12)] fits best to measured $\beta_d$ at angles between 70° and 110°.</td>
<td>1.76</td>
</tr>
</tbody>
</table>
be safely ignored. Note that for $\theta_0 < 50^\circ$ or $> 130^\circ$, the effect of the FOV is opposite, leading to an underestimate of the depolarization ratio using Eq. (17). However, this does not apply to our study.

E. Impact of Residual Particle Contamination on Light Scattering Measurements

Despite great care taken in preparing samples, it is extremely challenging to prepare pure water, and especially pure seawater, samples that are free from impurities [17, 51]. The residual particles, especially nanoparticles, are expected to be present in the samples. They will scatter light and their effects have to be subtracted before estimating the depolarization ratio of pure water or seawater samples. Using measurements at 90° as an example,

$$\delta = \frac{\beta_{h,m}(90) - \beta_{h,p}(90)}{\beta_{v,m}(90) - \beta_{v,p}(90)} = \frac{1}{1 - r_y(90)} \delta_m - \frac{r_x(90) - 1}{1 - r_x(90)} \delta_p,$$

where $\beta_{h,m}$ and $\beta_{h,p}$ are the horizontal and vertical components of the measured volume scattering function, $\beta_{v,m}$ and $\beta_{v,p}$ the horizontal and vertical components of the volume scattering function attributable to residual nanoparticles, and $r_y(90) = \beta_{v,p}(90)/\beta_{v,m}(90)$, $\delta_m = \beta_{h,m}(90)/\beta_{h,m}(90)$, and $\delta_p = \beta_{h,p}(90)/\beta_{h,p}(90)$. Here, $\delta_m$ represents the measured depolarization ratio if the effect of residual nanoparticles is not corrected, and $\delta_p$ represents the depolarization ratio of residual nanoparticles. Theoretically, the depolarization ratio for particles $\delta_p$ is zero only for a homogeneous size of much smaller than the wavelength of light, and any deviation from this condition, such as increased size or non-sphericity, would increase the depolarization ratio of particles. In Fig. 2, we compare $\delta_p$ simulated at 532 nm for particles of two very different shapes, sphere versus asymmetrical hexahedron [52, 53], of sizes from 1 to $\sim$300 nm and of two refractive indices, 1.02 and 1.20 relative to the refractive index of water. In addition, we also examined the effect of the FOV of a detector on $\delta_p$. In general, the depolarization ratio increases with particle size (more rapidly for spherical particles than non-spherical particles), with the particle refractive index, and with the FOV. Without knowing the particle characteristics (size, shape, and composition), it is impossible to know the exact value of depolarization ratio owing to the residual particles present in our samples. However, for particles of sizes $< 200$ nm, i.e., for samples filtered through a 0.2 $\mu$m filter, the values of $\delta_p$ (accounting for the effect of the DAWN detector’s field of view) are in the range of 0.0003 to 0.003. The upper value of 0.003 is $< 8\%$ of 0.039, the currently accepted depolarization ratio value for pure water. For $r_y(90) = 0.01$ to 0.03 (see our results presented below), Eq. (19) can be safely approximated as $\delta_p \approx 1 - r_y(90)$, which falls within a range of 0.97 to 0.99. This suggests that the contribution of residual nanoparticles, if not corrected, would cause an underestimation of 1% to 3% in the depolarization ratio of pure water. Note that the presence of particles leads to under- or overestimation of the depolarization ratio of water depends on the inherent depolarization ratio of the particles. If particles have an overall depolarization ratio lower than that of pure water, such as the residual nanoparticles in our samples, their presence leads to an underestimation. On the other hand, relatively large particles are expected to have a depolarization ratio greater than that of pure water, so their presence in the sample, if not corrected, would cause an overestimation of the depolarization ratio of pure water. We note that this trend associated with the presence of relatively large particles is consistent with recent measurements of samples from coastal and offshore oceanic waters, which show values of the degree of linear polarization of natural particle assemblages generally smaller than 0.8 with a tendency to decrease with increasing proportion of large particles [39].

3. RESULTS

A. Residual Particle Populations in the Pure Water and Master Salt Solutions

Two instruments, a ViewSizer 3000 (MANTA Instruments) and a NanoSight LM20 (Malvern Panalytical), were used to measure the size distribution of residual nanoparticles present in the prepared samples. Both instruments track Brownian motion of nanoparticles and estimate the size (diameter) of each particle, which is inversely proportional to the Brownian diffusion coefficient of particles [54]. Both instruments also have a capability to estimate nanoparticle concentration based on individual particle counting within the calibrated volume of sample. While the NanoSight uses only one laser source, the ViewSizer deploys three laser sources at different wavelengths, which generally improves both the size and concentration determinations of particles [55].

The NanoSight was used in parallel with the light scattering experiments. However, using the particle size distributions measured by the NanoSight led to an unrealistic situation where both vertical and horizontal components of the estimated particulate volume scattering functions were greater than
the ultrapure water and master salt solutions measured with salt compounds were the same. Specifically, all steps of the sample preparation including the same way as was done during the light scattering experiments. In separate, extreme care was used to prepare the samples in the although the measurements with the ViewSizer were done separately, extreme care was used to prepare the samples in the same way as was done during the light scattering experiments. Specifically, all steps of the sample preparation including the salt compounds were the same.

Figure 3 shows the size distribution of nanoparticles in the ultrapure water and master salt solutions measured with the ViewSizer. Clearly, neither the pure water samples nor the master salt solutions were particle free. The concentrations of particles were \( \sim 0.6 \) to \( 1.2 \times 10^6 \) mL\(^{-1}\), with the abundance of particles increasing towards smaller sizes of 0.05 to 0.08 \( \mu \)m. Note that the ViewSizer has an optimal range of detection of 0.1 to 1 \( \mu \)m, and therefore the measurements at sizes <0.1 \( \mu \)m have a relatively large uncertainty. Compared to the ultrapure water sample, the salt solution has slightly greater particle concentration, which is not surprising. Also, most of the additional particles introduced by salts are of sizes <0.1 \( \mu \)m. Filtration with a 20 \( \mu \)m filter reduced the particle concentrations by approximately 30% to 40% for both ultrapure water and seawater, which is also expected. However, the particles removed by the 20 \( \mu \)m filter, as observed by the ViewSizer, are mostly of sizes >0.1 \( \mu \)m. Again, this could be due to the optimal sensitivity range of the instrument (0.1 to 1.0 \( \mu \)m). Note that in our light scattering experiments for measuring the depolarization ratio, we used the ultrapure water directly without filtration and the 20 \( \mu \)m filtered master salt solutions to prepare seawater samples at various salinities.

Having determined the size distributions of nanoparticles from 20 to 1000 nm (Fig. 3), we now need the value of refractive index of these particles in order to estimate the particle contribution to the light scattering measurements. Unfortunately, direct determinations of the particle refractive index are not available; therefore, assumptions have to be made. Figures 4(a) and 4(b) show the FOV-averaged vertical and horizontal scattering components computed for the residual nanoparticles with an assumed hexahedral shape and refractive index of 1.02, 1.08, and 1.20 relative to water. Oceanic particles typically have a refractive index between 1.02 and 1.20 relative to water [56]. \( \beta_{h,p} \) and \( \beta_{h,p} \) shown in Figs. 4(a) and 4(b) for these two end values differ by a factor of approximately 40. \( \beta_{h,p} \) and \( \beta_{h,p} \) for a relative refractive index of 1.08 represent the approximate geometric mean of the \( \beta_{h,p} \) and \( \beta_{h,p} \) computed for the residual nanoparticles with a relative refractive index varying between 1.02 and 1.20. In the following analysis, we have assumed a relative refractive index of 1.08 for the residual nanoparticles.

Fig. 3. Particle size distributions (PSD) measured by the ViewSizer of residual nanoparticles in ultrapure water (UP), 20 nm filtered ultrapure water (20-nm UP), master salt solution (SS), and 20 nm filtered master salt solution (20-nm SS). The value in each legend entry is the total particle concentration (mL\(^{-1}\)) over particle diameter (\( D \)) range from 0.05 to 1 \( \mu \)m.

Fig. 4. The FOV-averaged (a) vertical and (b) horizontal components of particulate volume scattering function computed at a light wavelength of 532 nm for ultrapure water (solid lines) and the 20 nm filtered master salt solution (dotted lines) using the measured particle size distributions shown in Fig. 3 and assuming a hexahedral shape and relative refractive index of 1.02, 1.08, and 1.20 for particles suspended in water.
The filtration through the 20 nm filter effectively reduced the scattering by residual particles. As a result, the particulate scattering in our salt solution samples was approximately 50% of the scattering by residual particles in the ultrapure water [compare the solid curves and dotted curves in Figs. 4(a) and 4(b)]. However, both show the same scattering pattern with respect to the scattering angle, increasing towards forward angles and the scattering minimum for the horizontal component at 90°.

B. Correction of Light Scattering for Residual Particle Contamination in the Salt Solutions

The vertical and horizontal components of the volume scattering function resulting from residual nanoparticles in the prepared artificial seawater samples at various salinities were calculated as a weighted sum of the scattering attributable to residual nanoparticles in ultrapure water [solid curves in Figs. 4(a) and 4(b)] and in the master seawater sample [dotted curves in Figs. 4(a) and 4(b)]. The weighting factors are simply the mixing ratio of ultrapure water and the master salt solution. The sum was then subtracted from the measurement. As an example, Fig. 5 shows the correction for three samples measured in the first experiment: ultrapure water sample, the sample of salinity 16.15 g kg\(^{-1}\) prepared with a mixing ratio of 0.4, and the master salt solution of salinity 39.68 g kg\(^{-1}\).

Greater contributions to scattering by residual nanoparticles were found at forward angles, which is expected. This is one of the reasons that the scattering at those forward angles were not used in estimating the depolarization ratio of water. At 90°, the direct contributions by residual nanoparticles were about 1% to 3% to the vertical component, i.e., \(r_v(90°) = 0.01\) to 0.03 [see Eq. (19)], and only 0.02% to 0.05% to the horizontal component of the bulk volume scattering function measured for the samples. Without correction for nanoparticle contamination of samples, the depolarization ratio \(\delta\) would be underestimated by about 1% to 3% [Eq. (19)]. The particle contribution and hence the underestimation would be greater with the assumption of higher refractive index (8% to 9% for a relative refractive index of 1.20).

C. Estimating the Depolarization Ratio

We used the five methods listed in Table 2 to estimate the depolarization ratio of water. For Methods 2 to 5 that use measurements at multiple angles, we restricted the angular range from 70° to 110°, because at these angles the contribution of scattering by residual nanoparticles was relatively small (see Fig. 5) and the angular variations of horizontal component of scattering are relatively more significant [See Figs. 1(b) and 1(c)]. The comparisons of the estimates of the depolarization ratio using these five methods are shown in Fig. 6. In general, the estimates are consistent among different methods. Method 2 agrees with Method 3 the best because both are based on Eq. (16) and both slightly underestimate \(\delta\) compared with other methods. Because both Methods 4 and 5 are based on direct fitting of \(\beta_v(\theta)\) without using \(\beta_v(\theta)\), they agree with each other the best, and both slightly overestimate \(\delta\) compared with other methods. Method 1 slightly overestimates Methods 2 and 3 but slightly underestimates Methods 4 and 5.

D. Depolarization Ratio of Pure Water

The estimates of the depolarization ratio of pure water obtained in experiments 1 and 2 are summarized using the box and

![Fig. 5. Examples illustrating the correction of scattering by residual nanoparticles for the vertical (first row) and horizontal (second row) components of the volume scattering functions measured at three salinities in the first experiment. Blue: the measured scattering (before); red: estimated scattering attributable to nanoparticles (nano); yellow: the difference between the blue and red curves (after). In the legend, \(S\) salinity (g kg\(^{-1}\)); \(mr\) mixing ratio of salt solution, e.g., 0.4 means 8 mL (= 0.4 × 20) salt solution and 12 mL water for a total of 20 mL of final salt solution. All data are for a light wavelength of 532 nm.](image-url)
whisker plot in Fig. 7(a). A total of six measurements of pure water were conducted in the two experiments. For each of the five methods, the median values of the depolarization ratio are 0.040, 0.038, 0.039, 0.040, and 0.038, respectively, with an overall mean of 0.039 ± 0.001, the same as the value measured by Farinato and Rowell [4] when they used the narrower bandwidth filter to eliminate stray light. Disregarding the differences among the five methods and pulling all the estimates in Fig. 7(a) together, we derived a mean of 0.039 ± 0.002 for the depolarization ratio of pure water. These two mean values (0.039 ± 0.001 versus 0.038 ± 0.002) are not different statistically, and we will use 0.039 to represent the measured depolarization ratio of pure water in this study.

Using the measured depolarization ratio of 0.039, we further compared in Figs. 7(b)–7(d) the measured pure water volume scattering function and its horizontal and vertical components with the most recent pure water scattering model [33]. Before comparison, the measurements were scaled from the actual temperature at the measurement to a common temperature of 25°C using the ratio of scattering estimated at the two temperatures using the model. This temperature scaling is very small and does not affect the comparison results, which are summarized in Table 3 for five scattering angles of 72°, 81°, 90°, 99°, and 108°. Because we had six measurements of pure water, we also used pure water measurements to estimate the measurement uncertainty as the ratio of standard deviation to the mean value of the different measurements. The measurement uncertainties for $\beta_h$ have the greatest uncertainty on the order of 2% to 5%. This is not surprising because the signal level for the horizontal component of scattering is low. The uncertainties for $\beta_v$ and $\beta$ are much smaller and similar to each other (~0.6%). For comparison, Morel [34] reported a measurement uncertainty of 2% for pure water at $\beta(90)$. The comparison of our measurements with the Zhang and Hu [33] model of pure water scattering shows median differences of about ±3% for $\beta_h$, which, while relatively higher than those for $\beta$ and $\beta_v$, are still within the measurement uncertainty for $\beta_h$. For $\beta$, the differences between our measurements and the Zhang and Hu [33] model are similar to the differences reported between the Morel measurements and the Zhang and Hu [33] model.

With the estimated measurement uncertainty (Table 3), we can now estimate, through error propagation, the approximate uncertainty associated with the depolarization ratio obtained with each of the five methods (Table 2). Assuming the measurement uncertainties are uncorrelated between horizontal and vertical polarized measurements, we estimated that the uncertainties of the depolarization ratio obtained with
Methods 1 to 5 are 4.94%, 1.78%, 1.78%, 1.76%, and 1.76%, respectively (Table 2). These results indicate that Methods 2, 3, 4, and 5 are comparable and much better than Method 1.

E. Depolarization Ratio for Pure Seawater

The estimates of depolarization ratio obtained with the five methods at various salinities of water are shown in Fig. 8. All the methods seem to show a general increase of depolarization ratio with salinity, but there is significant scatter among the data. To better identify and confirm the intrinsic trend of the data, we applied three different least squares (LS) linear regression schemes to the data. The first was the ordinary LS linear regression using all the measurements (dash dotted line in Fig. 8). The second was the weighted LS linear regression using all the measurements (dotted line in Fig. 8). The Matlab function robustfit.m was used for the weighted LS regression [57], which implements an iterative procedure assigning equal weight at the beginning but subsequently re-estimating the weight for each data point. The points farther from model prediction in the previous iteration are given lower weight. We used the default bisquare weighting function. The third was the ordinary LS linear regression using data excluding the outliers that were identified in the second regression method (weighted LS) with a weight <0.9 (solid line in Fig. 8).

For each of the five methods of estimating the depolarization ratio [Figs. 8(a)–8(e)], the three regression results are very similar to each other regardless of whether or not the data points were weighted or if the outliers were excluded. This suggests that the general increasing trend of the depolarization ratio with salinity, which has been identified by all three regression schemes, appears to be valid despite the uncertainties in our experiments associated with residual nanoparticles in the samples and the relatively low signal of the horizontal component of the volume scattering function. The linear model shown in each panel of Fig. 8 is the result of the third regression scheme, i.e., ordinary LS regression excluding outliers, and it will be used below to represent the change of the depolarization ratio with salinity. It is of interest to point out that all intercept values are very close to the value 0.039 that we estimated for pure water, lending a certain level of confidence in using the linear model to approximate the variation of depolarization ratio with salinity over the range of salinities that we tested. However, the slopes of the regression results are slightly different among the five methods used to estimate the depolarization ratio. For Methods 1, 2, and 3 [Figs. 8(a)–8(c)], the predicted depolarization ratio values at salinity of 40 g kg\(^{-1}\) are about 10% greater than their respective values for pure water at 0 g kg\(^{-1}\). For Methods 4 and 5 [Figs. 8(d) and 8(e)], the increase is about 20%. This result is consistent with Fig. 6, showing that Methods 4 and 5 slightly overestimate δ compared with the other three methods. It is also of interest to point out that Methods 4 and 5, which derived greater change in depolarization ratio with salinity, rely on the measurements of β\(_h\) only, whereas Methods 1, 2, and 3 used measurements of both β\(_h\) and β\(_v\). The DAWN measures β\(_h\) and β\(_v\) with the same detectors but separately in time. Taking a ratio of the two, as done in estimating the depolarization ratio in Methods 1, 2 and 3, could either increase (if uncertainties associated with β\(_h\) and β\(_v\) are independent of each other; see Table 2) or decrease (if uncertainties associated with β\(_h\) and β\(_v\) covary with each other) the overall uncertainty. On the other hand, a significantly greater measurement uncertainty is associated with β\(_h\) than β\(_v\) (Table 3). Even though the salinity dependence derived...
from Methods 4 and 5 shows a better coefficient of determination ($R^2$) than the other three methods, we cannot categorically claim these results provide the best representation of the variation of depolarization ratio with salinity.

Based on the results presented in Fig. 8, we propose the following formula to represent the variations of depolarization ratio with salinity:

$$\delta(S) = 0.039 + a_1 \times S,$$  \hspace{1cm} (20)

where 0.039 represents the depolarization ratio of pure water and $a_1$ takes the value in the range from 0.0001 to 0.0002, probably with higher values more likely. This range represents a 10% to 20% increase of depolarization ratio for an increase of salinity from 0 to 40 g kg$^{-1}$. Currently, a salinity-independent depolarization ratio is assumed in modeling the light scattering by seawater [42]. Using Eq. (20), we calculated the changes in $\beta(90)$, $\beta_v(90)$, and $\beta_h(90)$ owing to the changes in depolarization ratio as a function of salinity and the results are shown in Fig. 9. Relative to the estimates based on a constant depolarization ratio, using Eq. (20) increases the estimates of $\beta(90)$ by 1% to 2%, $\beta_v(90)$ by 0.5% to 1%, and $\beta_h(90)$ by 10% to 20%. Our measurements show a clear increase with salinity of both the vertical and horizontal components as well as the total volume scattering function at 90°, all of which in general follow the model prediction. However, there is an increasing difference between the measurements and the model prediction with increase in salinity, particularly for $\beta(90)$ and $\beta_v(90)$. This could result from the remaining effect of residual particles for which we could not fully correct.

Morel [26,44] measured the light scattering at 90° of pure water and of seawater at a salinity of 38.4% at five wavelengths of 366, 405, 436, 546, and 578 nm. Assuming a power-law spectral dependence, i.e., $\beta(90, \lambda) = \beta(90, \lambda_0)(\lambda/\lambda_0)^\eta$, where $\lambda_0$ is the anchor wavelength and $\eta$ the spectral slope, we estimated $\beta(90)$ at 532 nm from Morel’s measurements of pure water and of seawater. The interpolated value of $\beta(90)$ at 532 nm varies depending on the choice of the anchor wavelength, and the range of the estimates obtained using each of the five wavelengths as an anchor is shown in Fig. 9(a). While our measurements of $\beta(90)$ agree with Morel’s measurements for pure water, our measurements of seawater are higher than his measurement, probably because of uncorrected residual nanoparticle scattering or because Morel used actual and not artificial seawater. Also, it seems that the model assuming an invariant $\delta = 0.039$ or $a_1 = 0.0001$ in Eq. (20) fits his measurements better.

4. DISCUSSION

Although the depolarization ratio of water is normally defined at a scattering angle of 90°, the anisotropy of water molecules influences the scattering at all angles. We used five methods to estimate the depolarization ratio from experimental measurements in this study. These methods have the same physical principle but differ in numerical method to retrieve the information. Because the magnitude of light scattering by water, and particularly its horizontal component at scattering angles near 90°, is extremely small and approaches the detection limit of the instrument that we used, using multiple methods allows (1) utilization of additional scattering measurements within a range of scattering angles; (2) reduction of uncertainty; and (3) cross-validation of the results. Figure 7(a) shows that our estimates of the depolarization ratio of pure water obtained from the five methods are quite consistent with each other, with the median values of each method varying from 0.038 to 0.040. The mean of these median values is $0.039 \pm 0.001$, in agreement with the value measured by Farinato and Rowell [4] more than 40 years ago.

In contrast to pure water, to our knowledge the depolarization ratio of seawater and its variation with salinity have never been

![Fig. 9. Scattering functions (a) $\beta(90)$, (b) $\beta_v(90)$, and (c) $\beta_h(90)$ calculated at a light wavelength of 532 nm and 25°C temperature as a function of salinity ($S$) using the Zhang et al. [42] model with three different depolarization ratio values: a constant value $= 0.039$ and variable values following Eq. (20) with $a_1 = 0.0001$ and $a_1 = 0.0002$. The circles represent the measured values. The black cross and error bar in (a) represent the range of the estimates (mean ± standard deviation) of $\beta(90)$ at 532 nm interpolated from Morel’s measurements [26,44] for pure water and for seawater at $S = 38.4\%$.

]
measured. Sweitzer [13] measured the depolarization ratio of several aqueous salt solutions, some of which are major components of sea salts, for concentrations up to 500 g kg⁻¹. For concentrations from 0 to 40 g kg⁻¹, Sweitzer's measurements showed that the depolarization ratio increases from 0.109 to 0.120 for NaCl, from 0.109 to 0.122 for CaCl₂, and from 0.109 to 0.132 for Na₂SO₄, whereas it decreases from 0.109 to 0.101 for KCl. The value of 0.109 was his measurement for pure water, and the values at 40 g kg⁻¹ were interpolated from his measurements. These results suggested that the depolarization ratio varies with salt concentration, but the extent of variation or even the direction of variation can differ among different salts. Among the 13 salt solutions that Sweitzer measured, only four show decreasing depolarization ratio with salt concentration, whereas the others all show an increasing trend. Using these values, we can roughly estimate the depolarization ratio of seawater by making two assumptions as utilized by Sweitzer (1926). First, we assume that the depolarization effects of pure water and sea salts are decoupled; for example, Sweitzer measured a depolarization ratio of 0.120 for NaCl at 40 g kg⁻¹, which includes a contribution of 0.109 associated with pure water and 0.011 (= 0.120 − 0.109) associated with NaCl. Our Eq. (20) also follows this assumption. Second, we assume that the depolarization effects attributable to different salts are directly additive, weighted by their respective mass ratios. We further assume that the depolarization ratio for MgCl₂ solution, which was not measured, is the same as for CaCl₂ (= 0.122 at 40 g kg⁻¹). Following the mass ratio of 0.6875:0.0211:0.0323:0.1451:0.1141 for NaCl:KCl:CaCl₂:MgCl₂:Na₂SO₄, we estimated that the increased depolarization ratio owing to sea salts at a salinity of 40 g kg⁻¹ is 0.0123. Using the value of 0.039 for pure water, this yields a total depolarization ratio of 0.0513 at 40 g kg⁻¹. Compared to Fig. 8 and Eq. (20), this estimate is slightly higher than our measurements and the model prediction at 40 g kg⁻¹. This is probably because our second assumption of direct additivity is invalid. Zhang et al. [58] simulated the scattering by different sea salt solutions and found that total scattering is greater than the sum of individual scattering contributions by sea salt solutions, a consequence of ionic interactions. It can be expected that the ionic interactions could also affect the depolarization ratio of seawater, for which the additive rule does not apply either. In addition, real seawater contains many other ionic species in varying proportions, in addition to the ones used to prepare samples in our experiments.

We have assumed a linear variation of the depolarization ratio with salinity. The measurements by Sweitzer [13] showed an overall nonlinear variation of the depolarization ratio with salt concentrations, but over a much greater range of concentrations from 0 up to 500 g kg⁻¹. For salt concentrations <50 g kg⁻¹, however, a linear trend could represent his measurements well. In addition, our results shown in Fig. 8 do not warrant a more complex regression model than the linear one.

By accounting for the variation of depolarization ratio with salinity, the estimated scattering can largely explain the observed horizontal component of the volume scattering function [Fig. 9(c)] but underestimates the observed vertical component and total volume scattering function [Figs. 9(a) and 9(b)]. As we alluded to earlier, this could be due to an unaccounted contribution by residual nanoparticles present in the samples. If this is the case, then this missing contribution by particles should be characterized by relatively greater vertical scattering and less horizontal scattering. In other words, these particles should have a relatively low depolarization ratio. Figure 2 shows that smaller particles with low refractive indices tend to have low depolarization ratios. Because the optimal detection range of the ViewSizer is 0.1 to 1 μm, one possible source of these missing particles could be in the small size range <0.05 μm where the ViewSizer is less sensitive to detect particles. At this moment, we do not have a method for effective quantitative sizing of the smallest nanoparticles <0.1 μm and therefore cannot resolve this uncertainty. However, this uncertainty mainly affects the absolute magnitude of scattering with a relatively small effect (1 to 3%) on the estimate of the depolarization ratio. Also, we point out that this uncorrected scattering by nanoparticles is associated mainly with seawater samples, because our measurements of β(90) for pure water agree well with Morel's measurement, but our measurements of seawater are greater than his seawater measurement [Fig. 9(a)].

The depolarization ratio was measured at a light wavelength of 532 nm in this study. Based on the theoretical derivation by Cabannes [3], Martin [12] argued that (1) the depolarization ratio for a liquid should decrease with wavelength in the visible and near-infrared spectrum, and (2) for different liquids, those liquids with stronger spectral dispersion of the refractive index should show stronger spectral variation of the depolarization ratio. From Table 1, Martin's first argument is supported by the measurements by Raman and Rao [7] and Cohen and Eisenberg [23], but not by the measurements of Pethica and Smart [21] and Kratohvil et al. [5]. Martin's second argument is inconsistent with the measurements by Raman and Rao [7], who found that water, which has the weakest spectral dispersion in the refractive index among the liquids that they measured, showed, however, the greatest spectral change in the depolarization ratio. Therefore, it is still an open question if or to what extent the depolarization ratio changes spectrally for water and seawater.

Because the depolarization ratio of the same substance would be lower in the vapor phase than in the liquid phase, it is expected that the depolarization ratio would decrease with temperature as the critical temperature is approached, which for water is 374°C. Cohen and Eisenberg [23] measured the scattering by pure water at temperatures from 0°C to 60°C and found a scattering minimum at ~22°C. Recently, Zhang and Hu [59] were able to reproduce this anomalous scattering behavior by assuming a constant depolarization ratio. We still do not know how the depolarization ratio of water might change within the temperature range of the oceans. But, if there is a change, the range of variation is most likely limited for the range of ocean water temperatures.

In conclusion, our measurements provided a mean depolarization ratio of 0.039 for pure water, which supports the value that is currently recommended for use by the hydrologic optics community. Our results suggest that the depolarization ratio of seawater increases slightly with salinity, reaching a value of about 0.045 to 0.050 at 40 g kg⁻¹, but with some uncertainty. A major challenge to further refining our knowledge on the effect of salinity on the depolarization ratio and potentially
improving quantitative data of this effect requires a preparation of samples of pure seawater or pure artificial seawater with varying salinity, which are free from nanoparticles and other contaminants, and improving the ability to quantify the nanoparticles and their properties in water.

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