Mueller matrix measurements of ocean water

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Abstract

Measurements of the complete polarized light scattering properties of ocean water have been made for scattering angles from 10° to 160°. The observed normalized Mueller matrices had six non-zero elements whose angular dependences were reminiscent of Rayleigh scatterers. The remaining 10 elements were zero at all scattering angles. The normalized measurements showed little variability with the location or depth of the sample even though total cross-sections varied by more than an order of magnitude. An average Mueller matrix is presented which represents ocean water scattering effects with a standard deviation of typically less than 10% over the various ocean locations and depths that we observed.

Introduction

Polarized light scattering measurements, (i.e. Mueller matrix measurements), of ocean water have been done by Beardsley[1] and by Kadyshevich.[2] The latter observed many effects that were indicative of hydrosol asymmetries or optical activity and were characteristic of particular ocean locations and/or depths. In order to more clearly understand the effects of light scattering in the ocean, we have developed an instrument[3,4] that makes these measurements much more rapidly and accurately than was possible with the instruments used previously. Briefly, our instrument uses four electro-optic modulators, two in the incident and two in the scattered light beams. These modulate the incident light through all polarization states and analyze the polarization of the scattered light, respectively. The four modulators are driven sinusoidally at 950 Hz, 9.5 kHz, 737 Hz, and 559 Hz; the sixteen Mueller matrix elements appear in the detected signal as the Fourier amplitudes at various independent linear combinations of the primary modulation frequencies. The entire matrix is divided by the first element S_{11} (the phase function) which typically varies over several orders of magnitude. This highlights the polarization effects, and restricts the normalized matrix elements to values $-1.0 \leqq S_{ij} \leqq 1.0$.

Experimental Results

Figures 1, 2, and 3 show the averages of the non-zero matrix elements measured for over 60 samples during 1983. These samples were from various locations and depths in the Atlantic and Pacific Oceans. For these results S_{12} and S_{21} were averaged together since they were always equal within experimental error, as were S_{33} and S_{44}.

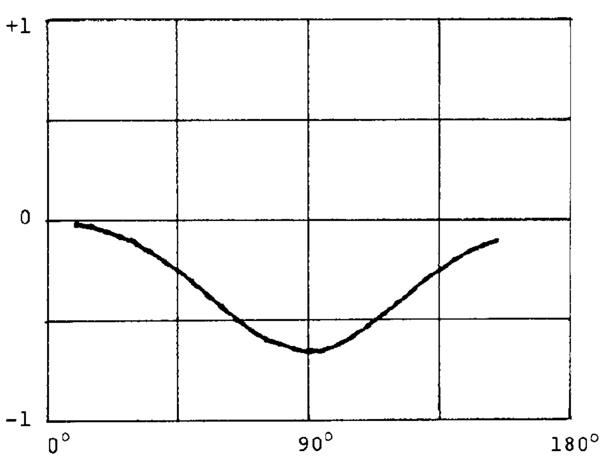

Figure 1. Matrix elements $S_{12}=S_{21}$.

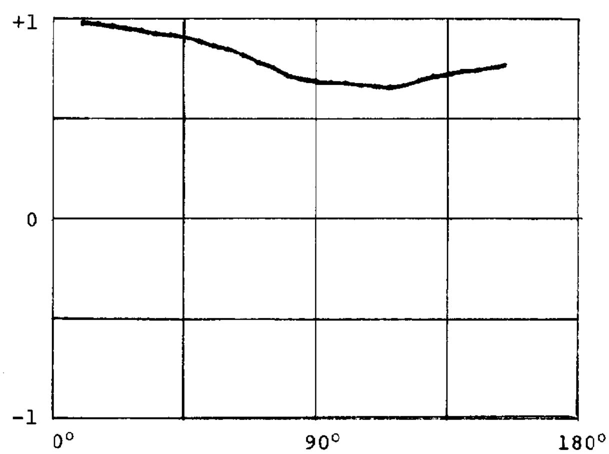

Figure 2. Matrix element S_{22}.

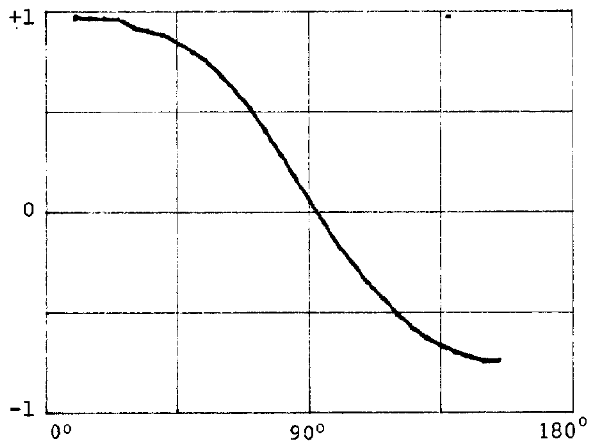

Figure 3. Matrix elements $S_{33}=S_{44}$

For easy reference this data is listed in Table 1 together with the standard deviations representing the variability over the ensemble of samples.

Table 1. Average Non-zero Matrix Elements and Standard Deviations for the Ensemble of Samples

Angle	$S_{12}=S_{21}$	σ	S_{22}	σ	$S_{33}=S_{44}$	σ
10	-.02	.03	.98	.05	.97	.07
15	-.03	.03	.97	.06	.97	.08
20	-.05	.03	.96	.05	.96	.07
25	-.08	.03	.95	.04	.96	.06
30	-.11	.03	.94	.04	.92	.06
35	-.16	.03	.93	.05	.90	.06
40	-.20	.03	.92	.05	.89	.06
45	-.25	.03	.91	.06	.84	.07
50	-.31	.04	.89	.05	.80	.08
55	-.37	.04	.86	.05	.75	.08
60	-.43	.05	.85	.06	.68	.09
65	-.49	.05	.82	.06	.60	.10
70	-.55	.06	.78	.07	.51	.10
75	-.60	.07	.76	.08	.41	.09
80	-.62	.08	.72	.10	.30	.10
85	-.65	.09	.70	.10	.18	.09
90	-.66	.10	.69	.11	.07	.10
95	-.66	.09	.68	.10	-.05	.09
100	-.63	.09	.68	.10	-.17	.10
105	-.59	.09	.67	.10	-.26	.11
110	-.54	.08	.66	.11	-.36	.11
115	-.48	.07	.66	.12	-.43	.13
120	-.43	.06	.67	.11	-.51	.12
125	-.37	.05	.69	.09	-.58	.12
130	-.31	.04	.71	.09	-.63	.12
135	-.26	.03	.72	.07	-.67	.13
140	-.21	.03	.74	.06	-.70	.11
145	-.16	.03	.75	.09	-.72	.12
150	-.13	.03	.76	.08	-.75	.11
155	-.11	.03	.77	.06	-.74	.09

The matrix elements S_{13}, S_{14}, S_{23}, S_{24}, S_{31}, S_{32}, S_{34}, S_{41}, S_{42} and S_{43} are zero to within 3-4% at all scattering angles. Important features are both the similarities and the differences of the angular dependences with those of Rayleigh scatterers. The latter have zeros for the same matrix elements as those observed to be zero in the ocean. The matrix elements $S_{12}=S_{21}$ have an angular dependence similar to that of Rayleigh scatterers but only reach -0.6 to -0.7 at 90° rather than -1.0 which corresponds to the complete polarization of Rayleigh scattering. Matrix element S_{22} which is unity at all scattering angles for Rayleigh scatterers falls off to a broad minimum around 110° in the ocean data. This effect is to be expected for randomly oriented non-spherical particles. The matrix elements S_{33} and S_{44} differ from Rayleigh scatterers by reaching values of only -0.7 to -0.8 rather than -1.0 at backscattering angles. Further, these elements cross the abscissa at scattering angles from 90° to 95° rather than precisely 90°.

This last effect may, in fact, provide useful information about the oceanic hydrosols as indicated by the results for two samples from different depths at one location. One depth, at 143 meters (5 meters from the bottom), corresponded to a minimum in a transmissometer reading and to a very low chlorophyll fluorescence reading. Thus, the particulates were mostly sediment or detrital material with very little viable phytoplankton. For samples from this depth S_{33} and S_{44} crossed the abscissa at 90°. The other samples were from a depth of 28 m which corresponded to a low transmissometer reading and a high chlorophyll fluorescence indicating a relatively high level of viable phytoplankton. For these samples S_{33} and S_{44} crossed the abscissa at 95°. Although small, this effect was rigorously established[5] by cross-checking it against Rayleigh scattering standards before and after each measurement. It should be noted that for ocean samples this crossing has been observed to occur at various angles from 90° to approximately 95° but never at angles less than 90°.

Comparisons to the previous work

Our results are qualitatively similar to those of Beardsley[1]; however, they differ markedly with the results presented in the series of papers by Kadyshevich.[2] Most important, we do not observe a large number of non-zero off-diagonal elements as they do. Nor do we observe the largest variability in S_{12} and S_{21} at 25°-35°, rather we observe the largest variability in these matrix elements at 90° as indicated by the standard deviations in Table 1. To put these discrepancies in proper perspective it is important to note that we have developed a "new generation" instrument for this work. We require less than 4 minutes for a complete matrix measurement as compared to about 2 hours with the previous instruments. Consequently, we can and do regularly check the operation of the instrument by measuring the matrix of a Rayleigh scattering standard. These considerations are especially important since this type of measurement is extremely prone to systematic errors.

However, we do agree quantitatively with their results for the magnitude of S_{12} and S_{21} at 90° and with their observation that S_{33} and S_{44} cross the abscissa at 90°-95°.

Conclusions

The Mueller matrix for ocean water has a much simpler form than some previous measurements have indicated. Since it shows relatively little variability with different ocean locations and depths, our measurements were averaged to obtain a representative Mueller matrix for ocean water. This representative matrix provides essential input into any calculations to determine radiation transfer in the ocean and is relatively independent of location or depth.

Acknowledgements

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