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MONTE CARLO SIMULATION OF LASER BACKSCATTER FROM SEA WATER. (U)  
JAN 82 B W KOERBER, D M PHILLIPS

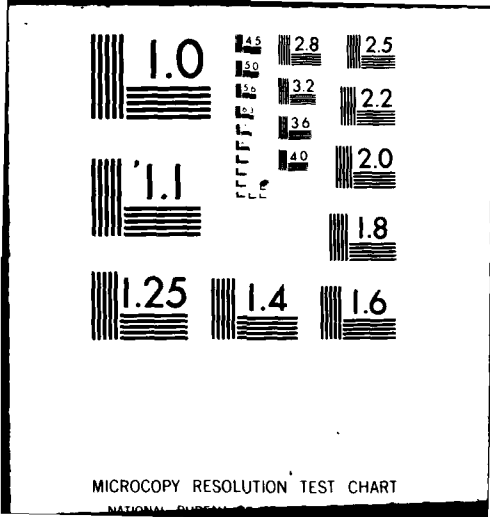
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TECHNICAL REPORT  
ERL-0224-TR

MONTE CARLO SIMULATION OF LASER BACKSCATTER FROM SEA WATER

B.W. KOERBER and D.M. PHILLIPS

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TECHNICAL REPORT

ERL-0224-TR

MONTE CARLO SIMULATION OF LASER BACKSCATTER  
FROM SEA WATER

B.W. Koerber and D.M. Phillips

S U M M A R Y

A Monte Carlo simulation study of laser backscatter from sea water has been carried out to provide data required to assess the feasibility of measuring inherent optical propagation properties of sea water from an aircraft. The possibility was examined of deriving such information from the backscatter component of the return signals measured by the WRELADS laser airborne depth sounder system. Computations were made for various water turbidity conditions and for different fields of view of the WRELADS receiver. Using a simple model fitted to the computed backscatter data, it was shown that values of the scattering and absorption coefficients can be derived from the initial amplitude and the decay rate of the backscatter envelope.



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## 1. INTRODUCTION

Several experimental studies have recently been carried out at the Defence Research Centre Salisbury to determine the effects of water turbidity on the performance of the WRELADS laser airborne depth sounder(ref.1-3). Combined aircraft and boat trials were held to obtain simultaneous measurements of return signals by the green receiver of the WRELADS system and of the attenuation coefficient of the waters in which the trials were conducted. An empirical relationship was established between the maximum depths measured by the WRELADS system and the values of attenuation coefficient of the sea water. Analysis of the backscatter component of the green receiver return signals indicated that the amplitude and the decay rate of these signals might be suitable parameters for determining water turbidity from an aircraft.

To provide further insight into the feasibility of measuring optical properties of sea water from an aircraft, Monte Carlo simulation studies of laser backscatter from sea water have been undertaken using a program developed at DRCS for use on a large digital computer. Information was obtained from this model of the magnitude of the backscattered light signal versus time produced at an airborne receiver from a pulse of laser light. Computations were performed covering a large range of water turbidity conditions corresponding to the range in which WRELADS is operated. Computed values of backscatter amplitude and backscatter decay rate were then compared with the values of the scattering, absorption and attenuation data used as input to the program. Using these results, it was possible to confirm the feasibility of deriving information of light propagation parameters for sea water from airborne measurements of laser backscatter and to establish experimental conditions under which valid information can be obtained.

## 2. MONTE CARLO MODEL

### 2.1 Simulation of WRELADS operation

The computations of backscattered light from a laser beam required for this study were made using a Monte Carlo model developed for simulation studies of the WRELADS system. This model has been programmed for the IBM 370 computer which provides adequate speed and storage capacity to handle the large number of complicated calculations required.

During operations of the WRELADS equipment (see figure 1), the airborne laser transmitter and optical receiver are flown at a height of 500 m above the sea surface. The narrow transmitter beam consisting of infra red and green components produced by a frequency doubled Nd:YAG laser is directed down at the sea in a series of rapid pulses of short duration. The 1064 nm infra red beam is reflected at the water surface and the return signal measured by an infra red receiver, providing a datum for the depth sounding measurement. The 532 nm green beam penetrates the water medium to the sea bottom where a signal is reflected back to the green receiver which has an adjustable field of view covering an area of up to 10 m radius at the sea surface. An estimate of the depth of the sea bottom is obtained from the time interval between the surface and bottom reflections.

The return signal at the green receiver consists of four components: the surface reflection, backscatter, the sea bottom reflection and general background reflected sunlight. It is the backscatter signal produced by multiple scattering in the water between the surface and sea bottom that is of relevance to this present investigation into the feasibility of monitoring optical properties of water from an aircraft. The modelling and analysis of these backscatter signals are described in the following sections.

## 2.2 Description of the model

For the purpose of the modelling (see figure 2), the laser transmitter beam is assumed to be a vertical, parallel light beam of infinitesimal width. The laser emission is modelled as an instantaneous pulse of light. To simplify the analysis, flat sea conditions (no waves or ripples) are assumed.

The model simulates the random passage in the water of individual photons from the transmitter light beam through series of scatterings until the photons reach the boundaries of the sea water medium or move laterally well outside the field of view of the airborne optical receiver. For each segment of a photon trajectory, values are determined for the distance travelled before scattering and for the scattering angles by making random selections from cumulative probability data for these parameters. Random numbers required for this procedure are generated using the multiplicative congruential method in a subroutine of the program. Weighting factors are computed for each photon trajectory to account for the absorption losses along that path. Transit times through the water are computed for each photon path. After the computations have been repeated for a large number of photons, a space-time map is built up of the distribution of light flux in the water.

For each photon that is backscattered from the sea water, tests are carried out in the program to determine whether this photon is within the field of view and travelling towards the entrance aperture of the airborne receiver. Allowance is made for a change in direction at the sea surface due to refraction at this interface. Totals are kept of the numbers of photons (weighted for the effects of absorption) collected at the receiver during successive 5 ns intervals of photon travel time. To examine the effect of changing the field of view of the receiver, sub-totals are kept of the numbers of these photons collected from concentric annular regions at the sea surface having radii 0.25, 0.50, 1.0, 2.0, 5.0 and 10.0 m.

Very large numbers of photon trajectories must be computed to reduce the chance variations produced in the results due to the random Monte Carlo process used in this simulation study. In order to keep computing times within manageable limits, it was decided to substantially increase the effective collecting area of the optical receiver in the model, thereby producing considerable smoothing of results by averaging over the much larger area. Hence in the model, the photons are counted as they arrive in the concentric annular regions in the receiver aperture plane having radii 10, 20, 30, 40 and 50 m. Totals obtained for these larger areas can be scaled to provide results relevant to the actual receiver size (180 mm diameter).

The computer program is executed in a series of separate runs and after each run the output data are combined in a single data set. As each additional run is carried out, an assessment is made of the magnitude of the random errors in the data due to the Monte Carlo process. These errors are progressively reduced as the data sample size is increased. The computations are continued until the random errors are reduced to an acceptable level.

## 3. CALCULATIONS OF LASER BACKSCATTER

### 3.1 Data on optical properties of water

The computations of backscattered light from a laser beam were carried out for a range of water turbidity conditions from clear water to the highest

turbidity in which WRELADS can be operated effectively. Computations were performed for values of attenuation coefficient,  $c$ , of 0.1, 0.5, 2.0 and 5.0  $m^{-1}$ .

The magnitude of the contributions of absorption and scattering to these levels of attenuation were determined by referring to an experimental study of absorption versus attenuation carried out by DRCS during 1979 and 1980. In this study, a series of in situ measurements were made at several wavelengths of the absorption coefficient,  $a$ , and the attenuation coefficient,  $c$ , in waters of various turbidity in the Gulf of St Vincent. The measurements were made from a small boat using an absorption meter instrument (figure 3) and a transmissometer instrument (figure 4, and also see reference 4). Both instruments were developed and made at DRCS: the absorption meter is based on a design produced at the Stanford Research Institute(ref.5) and the transmissometer on a design by Austin and Petzold at the Scripps Institution of Oceanography(ref.6). Data of  $a$  versus  $c$  measured at a wavelength of 530 nm are shown in figure 5. For comparison, several examples of data measured by the Scripps Institution of Oceanography(ref.7) are included in the figure; there is general agreement between the two sets of data, but the values of  $a$  appear to be somewhat higher at small  $c$  in the Scripps' data. The values of  $a$  used in the Monte Carlo study were obtained from the regression line fitted to the DRCS data. Values of the scattering coefficient,  $b$ , were then calculated by subtracting the values of  $a$  from the corresponding values of  $c$ . Table 1 provides a list of the values of  $c$ ,  $a$  and  $b$  used in the Monte Carlo study.

TABLE 1. INPUT DATA ON OPTICAL PROPERTIES OF WATER

Attenuation Coefficient $c$ ( $m^{-1}$ )	Absorption Coefficient $a$ ( $m^{-1}$ )	Scattering Coefficient $b$ ( $m^{-1}$ )
0.1	0.0725	0.0275
0.5	0.128	0.372
2.0	0.337	1.663
5.0	0.754	4.246

Information of the volume scattering function,  $\beta(\theta)$ , was obtained from experimental data published by the Scripps Institution of Oceanography(ref.7). In the model, basic  $\beta(\theta)$  data were provided in the form of tables for seven representative curves measured at a wavelength of 530 nm in waters having a range of values of  $b$  from 0.009 to 1.818  $m^{-1}$ . During the operation of the model, appropriate data of  $\beta(\theta)$  were generated for the particular values of  $b$  required in the simulation study by interpolation (or extrapolation) of the tabulated basic data. The accuracy of this operation was significantly improved by first normalizing the  $\beta(\theta)$  data by dividing by the corresponding values of  $b$  to produce nearly constant-valued functions versus  $b$  for each of the tabulated values of the scattering angle,  $\theta$  (examples are shown in figure 6). Values of cumulative probability,  $P(\theta)$ , were then obtained from the derived  $\beta(\theta)$  data using the trapezoid integration technique to evaluate the following equation:

$$\begin{aligned}
 P(\theta) &= \frac{2\pi \int_0^\theta \beta(\theta) \sin\theta \, d\theta}{2\pi \int_0^\pi \beta(\theta) \sin\theta \, d\theta} \\
 &= \frac{2\pi \int_0^\theta \beta(\theta) \sin\theta \, d\theta}{b}
 \end{aligned}
 \tag{1}$$

The values of  $P(\theta)$  obtained for  $b = 1.663 \text{ m}^{-1}$  are shown in figure 7.

### 3.2 Analysis of computed backscatter data

The amplitude of the backscattered light signal decays exponentially with time measured from the entry of the laser beam into the water. In clear water, the initial amplitude of the signal is small and the decay time is long, but in turbid water, the initial amplitude is large and the decay time is short. In a previous study of the backscatter signals measured by the WRELADS system (ref.2), a simple model had been suggested to describe the shape of the backscatter signal. The amplitude of the backscattered light is given by:

$$B_Z = B_0 \exp(-2k_b Z) \tag{2}$$

where  $B_0$  is the initial backscatter signal,

$k_b$  is the backscatter attenuation coefficient,

and  $Z$  is the depth below the water surface.

Signals recorded as a function of time can be transformed to a function of depth using the value of the velocity of light in water ( $2.245 \times 10^8 \text{ ms}^{-1}$ ) as the conversion factor.

The purpose of the Monte Carlo simulation study of laser backscatter was to provide data against which the validity of the above simple model (or a modified form of it) could be assessed. It was expected that the simulation study results would provide a means of establishing relationships between the model parameters  $B_0$  and  $k_b$  and the parameters

describing the inherent optical properties of the water viz,  $a$ ,  $b$ ,  $c$ , and  $\beta(\theta)$ . As a step towards achieving this aim, the simple backscatter model was developed a stage further. Assuming the backscattered light originating from just below the water surface is essentially light that has been scattered once only, theory indicates that the parameter  $B_0$  would be

proportional to  $\beta(180^\circ)$  and hence  $\beta(180^\circ)$  can be evaluated from  $B_0$ . Values

of  $\beta(180^\circ)$  can in turn be converted to values of  $b$  using an empirical (non-linear) relationship between these parameters derived from the published Scripps' data (figure 8). Thus the model was extended to provide information of  $b$  from the values of  $B_0$  obtained by fitting the model to the

backscatter data. Any significant deviations of these estimated values of  $b$  from the actual values used as input to the Monte Carlo model could then be attributed to a breakdown of the simple model due to the effects of multiple scattering. Fitting the model to the Monte Carlo backscatter data

was carried out by first taking logarithms of equation 2:

$$\ln B_z = \ln B_0 - 2k_b Z \quad (3)$$

Linear regression analysis was then used on the backscatter data computed for 5 ns intervals during the initial 100 ns of photon travel time (corresponding to a depth of 11.23 m). For each time interval, an 'effective depth' was calculated allowing for the exponential decrease of light flux collected during the interval. From the fitted regression line, values were obtained of  $k_b$  and  $\ln B_0$  and hence of  $b$ . The standard errors in these parameters were computed from the magnitude of the spread of the data points about the regression line (this spread is due mainly to the random Monte Carlo process). The analysis procedure was carried out on the data obtained for each of the six different receiver fields of view for which the Monte Carlo simulations had been performed (for the two smallest field of view settings, only data collected in the innermost receiver annuli were used to avoid 'vignetting effects' on the backscattered light produced at the greater depths).

#### 4. RESULTS

The Monte Carlo computations were continued until the random errors in the results were reduced to an acceptable level. It was found that these errors had levelled off after 12 runs, each of duration of approximately 10 min CPU time. The final errors in the estimated values of  $a$  and  $b$  obtained for the maximum receiver field of view (10 m radius) were about 3 and 12% respectively for  $c = 0.5, 2.0$  and  $5.0 \text{ m}^{-1}$ . The errors were approximately doubled for  $c = 0.1 \text{ m}^{-1}$ . The total numbers of photon trajectories computed were 16.8, 3.0, 0.6 and 0.6 millions respectively, for  $c = 0.1, 0.5, 2.0$  and  $5.0 \text{ m}^{-1}$ .

Figure 9 shows the numbers of backscattered photons versus time collected at the airborne receiver. Data are plotted for the maximum receiver field of view (10 m radius). Also shown on the figures are the regression lines fitted to the backscatter data.

Computed values of the backscatter attenuation coefficient,  $k_b$ , versus radius of the receiver field of view are shown in figures 10 to 13. The values of  $k_b$  are seen to lie between the values of the absorption coefficient,  $a$ , and the attenuation coefficient,  $c$ . As the field of view of the receiver is increased, the value of  $k_b$  progressively decreases and tends to the value of the absorption coefficient at the maximum field of view setting (10 m radius). The trend shown in these data is statistically significant, as is indicated by the relatively small standard errors (shown as error bars in the figures) applying to the data.

The computed values of the scattering coefficient,  $b$ , versus radius of the receiver field of view are shown in figure 14. These values are distributed on both sides of the actual values of  $b$  used as input to the Monte Carlo model. The standard errors in the computed values are of the same magnitude as the differences between the computed and actual values. Therefore, it is inferred that the apparent variations are due to chance and the computed values are valid estimates of the scattering coefficient (the source of these chance variations is largely from the random Monte Carlo process). However, this

general conclusion possibly may not be valid for the data obtained for  $c = 5.0 \text{ m}^{-1}$ . The computed scattering coefficient data for this turbidity level appear to have a significant bias towards higher values than the actual input value. This may be evidence that the simple model of backscatter does breakdown at very high water turbidity levels due to the effects of multiple scattering. Nevertheless, the model appears to be adequate over virtually the entire range of water turbidity conditions in which the WRELADS system is normally operated.

## 5. CONCLUSIONS

The following conclusions are obtained from the results of the Monte Carlo simulation study of backscatter from a laser beam.

(1) It is feasible to monitor optical propagation properties of sea water by making measurements of laser backscatter from an aircraft. The WRELADS system is suitable for such measurements.

(2) The simple model of backscatter examined in this study is adequate to describe the shape of the backscatter signal over the range of water turbidity conditions in which WRELADS is operated.

(3) Accurate estimates of the absorption coefficient,  $a$ , can be obtained from measurements of the decay rate of the backscatter envelope providing an adequately large receiver field of view is used. For the WRELADS receiver operating at a height of 500 m, the greatest accuracy is obtained using the maximum field of view of radius 10 m at the sea surface.

(4) Measurements of the initial magnitude of the backscatter signal can be used to obtain estimates of the scattering properties of sea water. Accurate estimates can be directly obtained of the volume scattering function at  $\theta = 180^\circ$ . These in turn can be converted to values of the scattering coefficient,  $b$ , using an empirical (non-linear) relationship between these parameters. The accuracy of the estimates of  $b$  will depend, of course, on the general applicability of the empirical relationship used for the conversions. This is an area where more experimental data would be beneficial.

(5) Further experimental studies should be carried out using the WRELADS system to develop the measurement techniques required for routine monitoring of optical properties of sea water from an aircraft. An assessment is required of the accuracy of data obtained under normal operating conditions.

## 6. ACKNOWLEDGEMENTS

The authors wish to acknowledge the assistance provided by Mr W. Graveney in maintaining and operating the absorption meter and transmissometer equipment used by OT Group for measurements of absorption coefficient versus attenuation coefficient.

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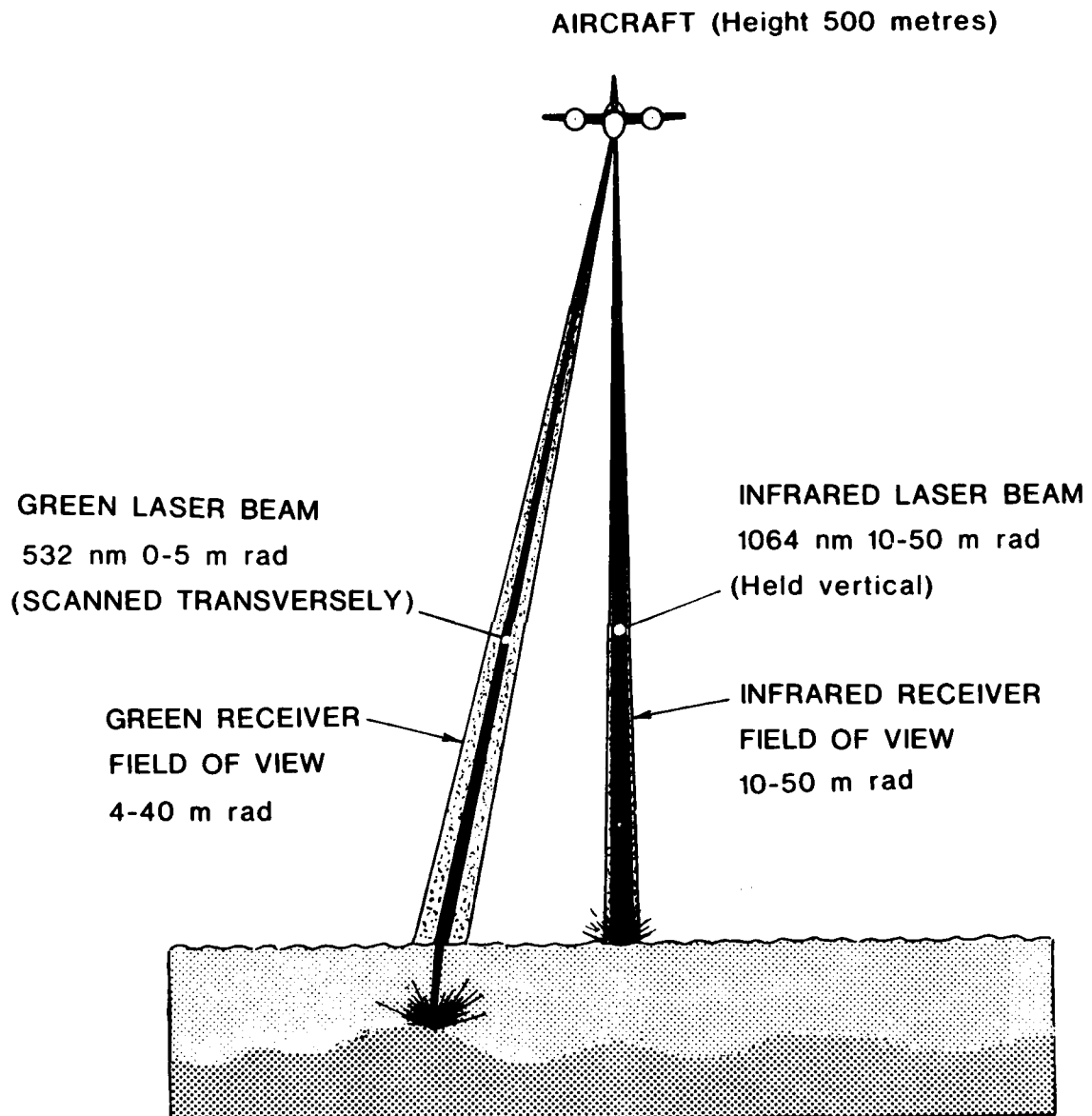


Figure 1. Schematic diagram of WRELADS system

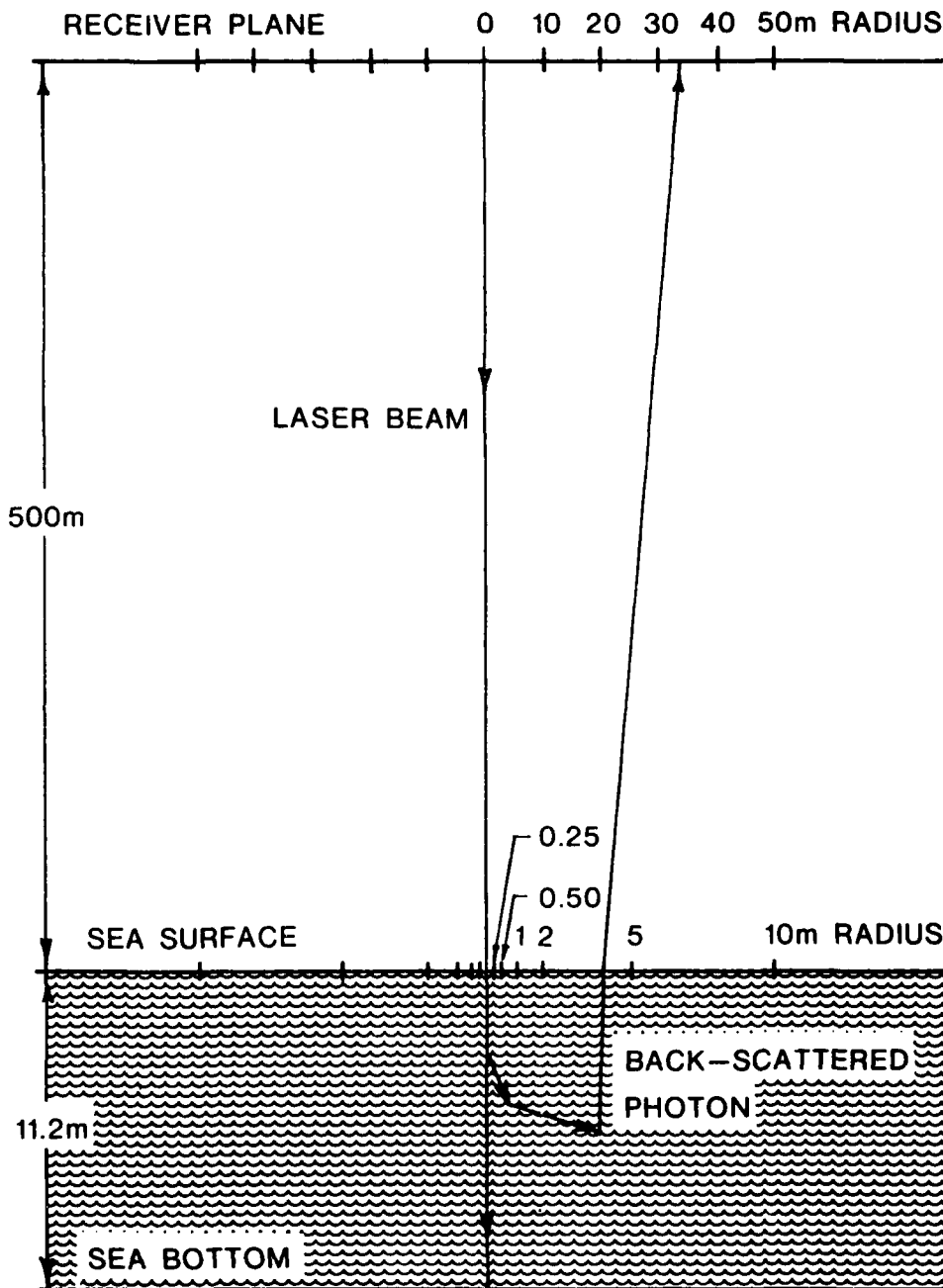


Figure 2. Geometry used for Monte Carlo simulation model

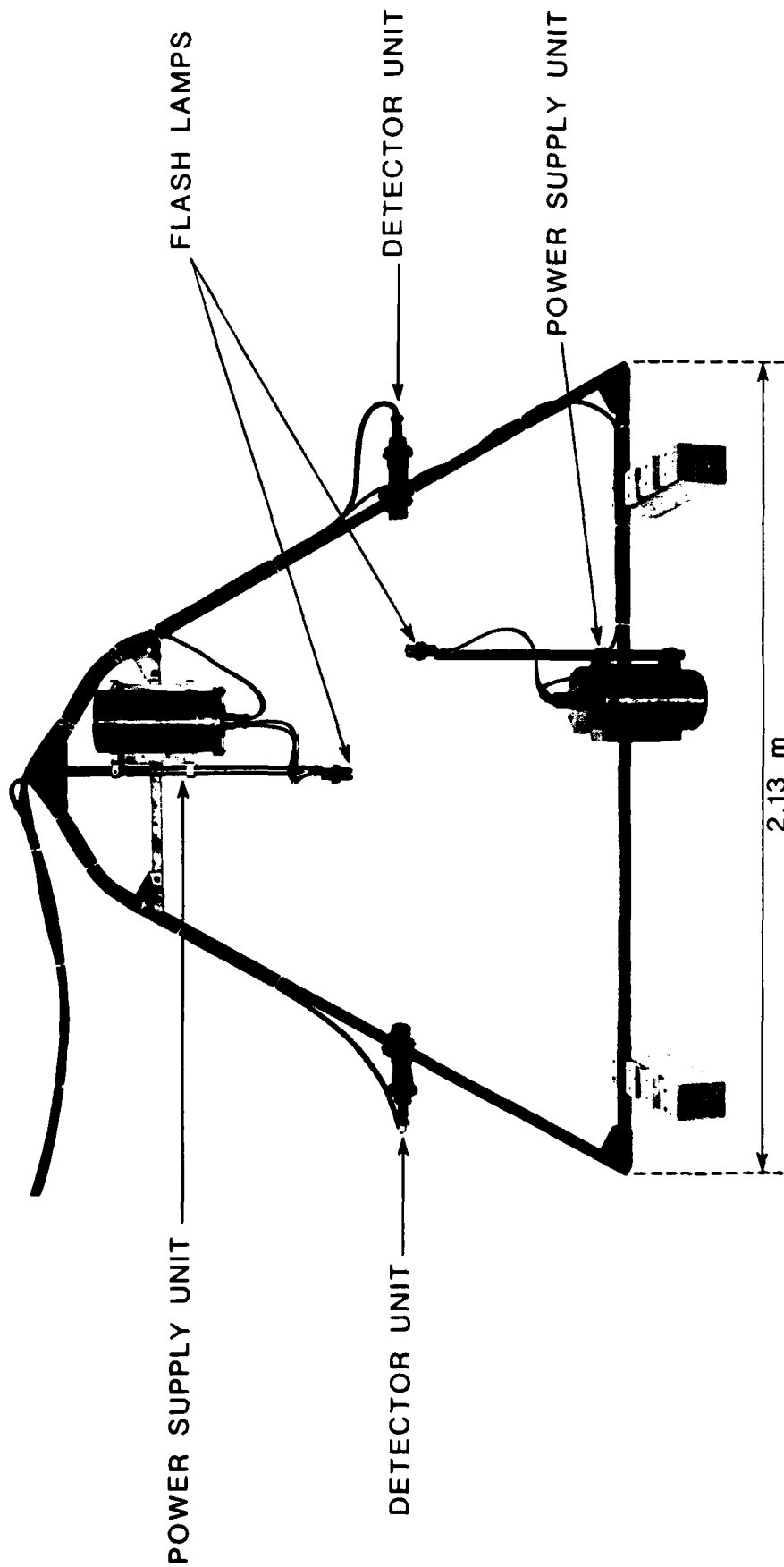


Figure 3. The underwater absorption meter

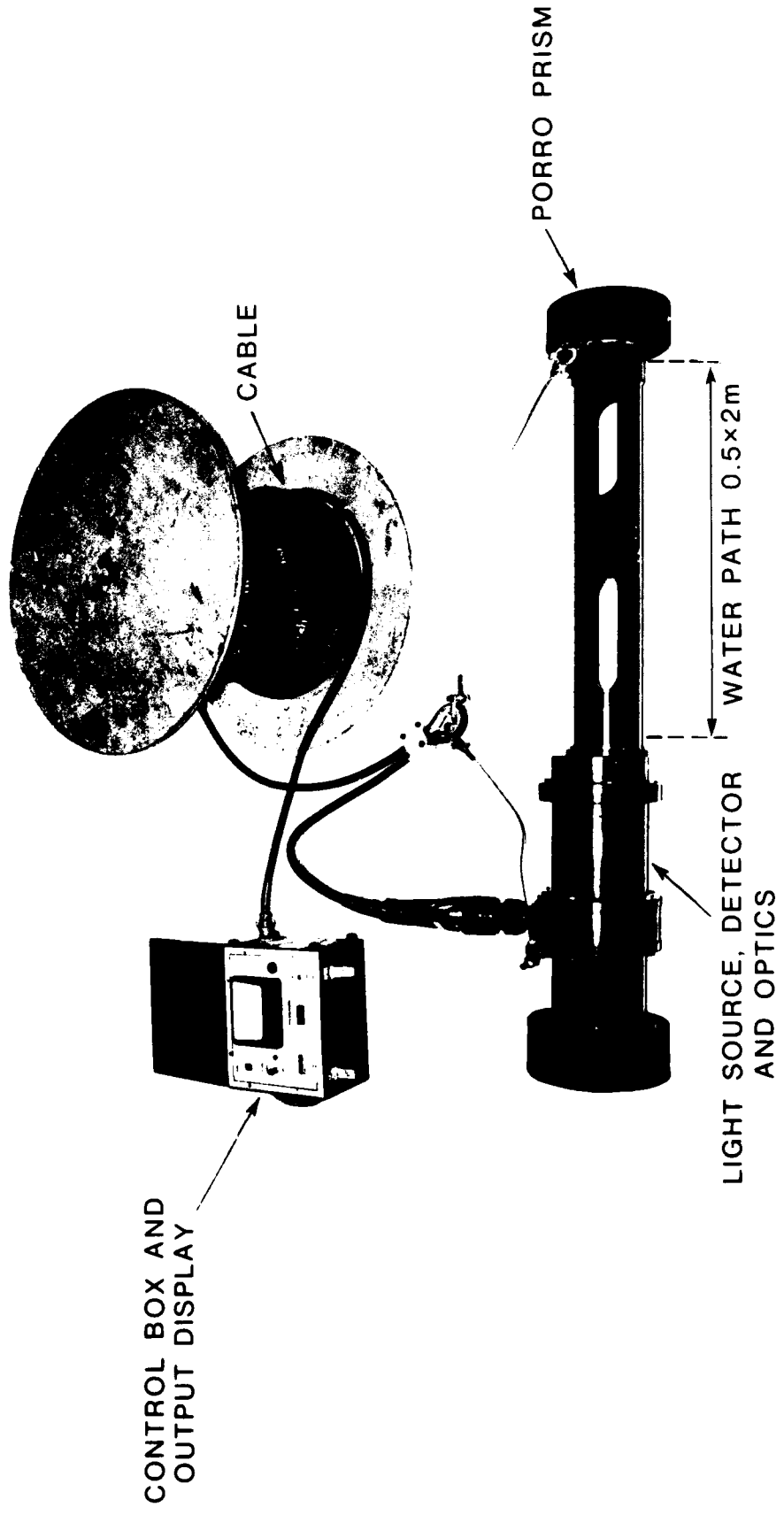


Figure 4. The underwater transmissometer equipment

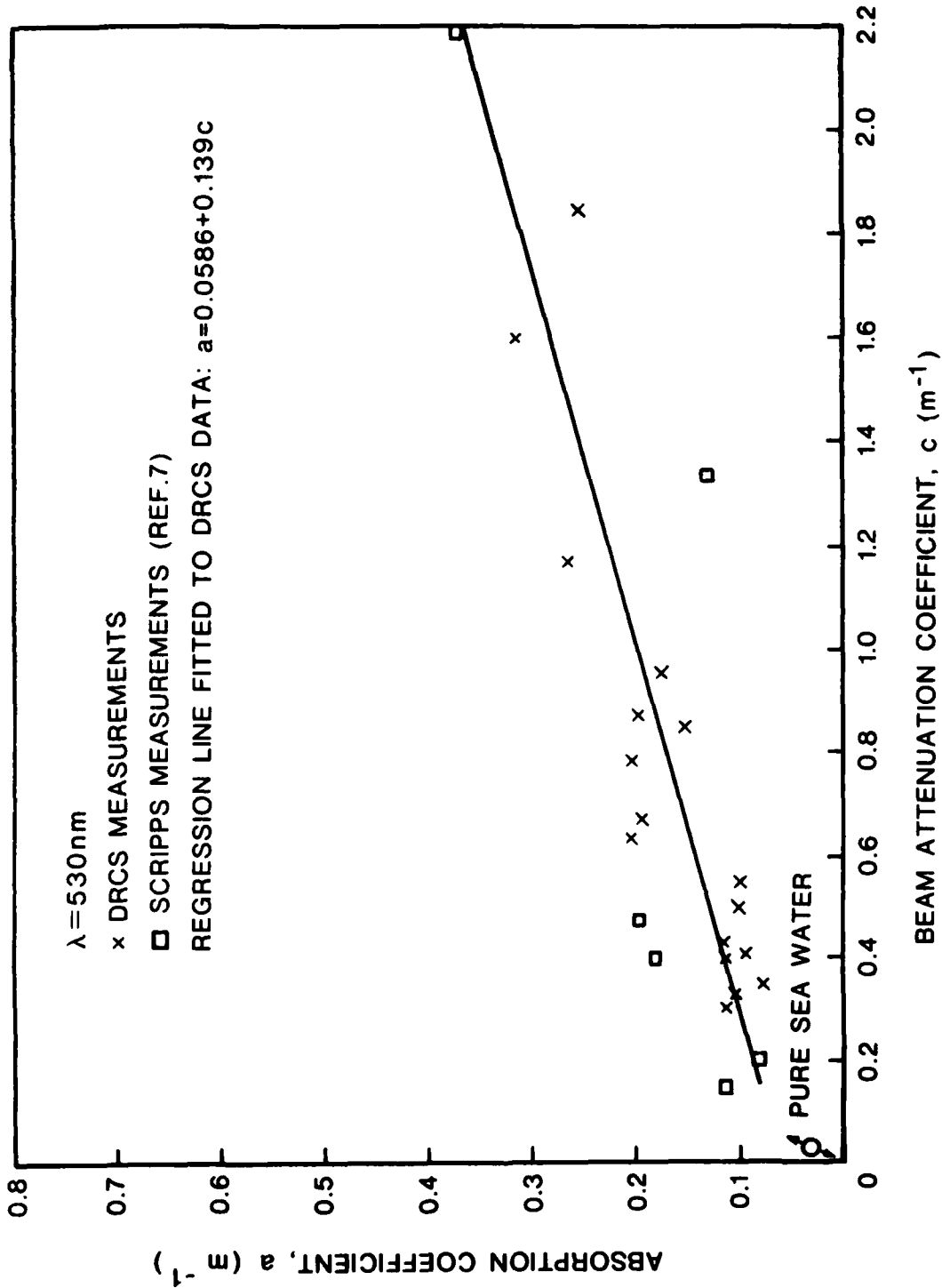


Figure 5. Comparison of measured values of absorption coefficient and attenuation coefficient in various waters

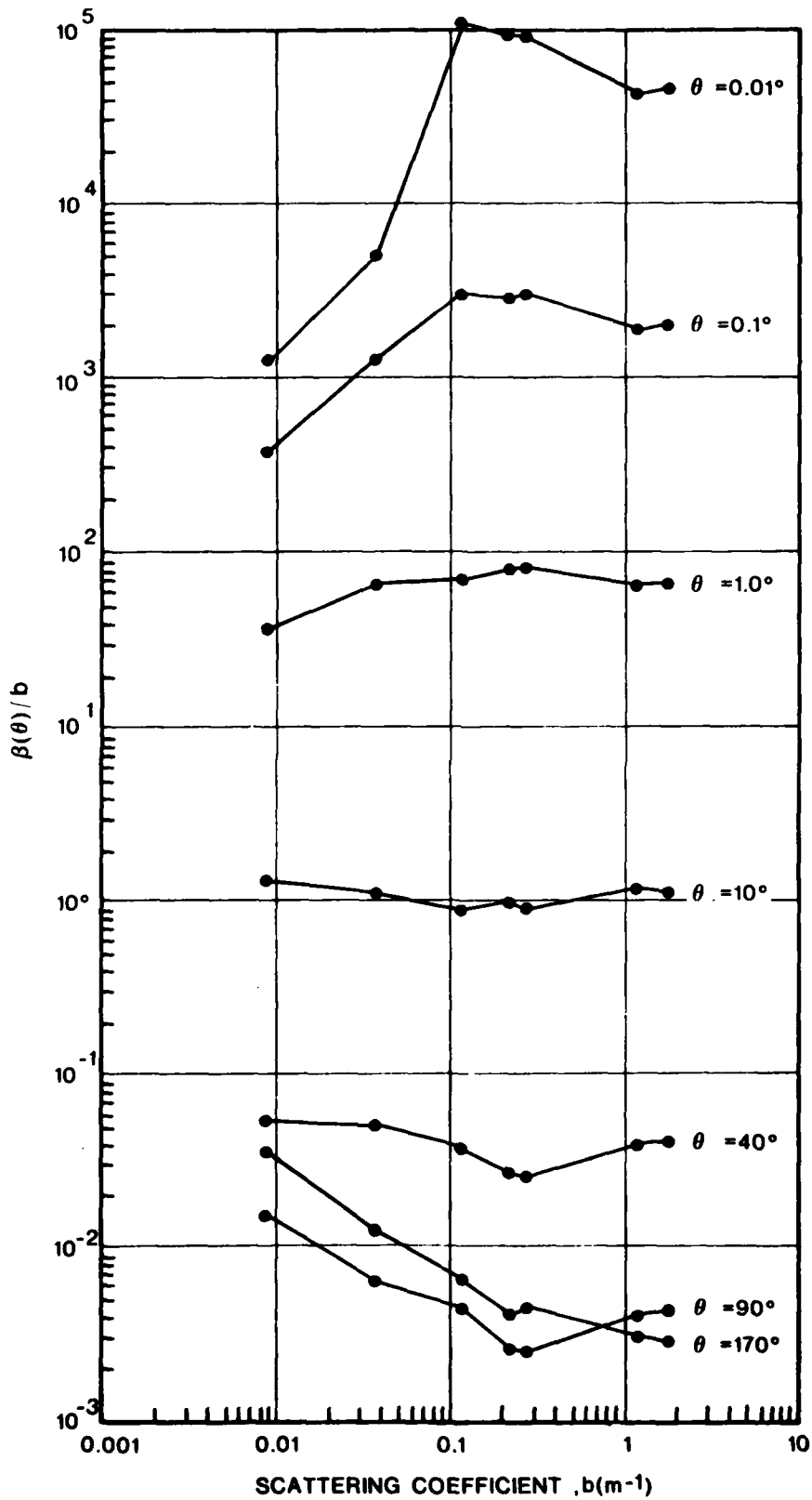


Figure 6. Normalised volume scattering function versus scattering coefficient (adapted from reference 7)

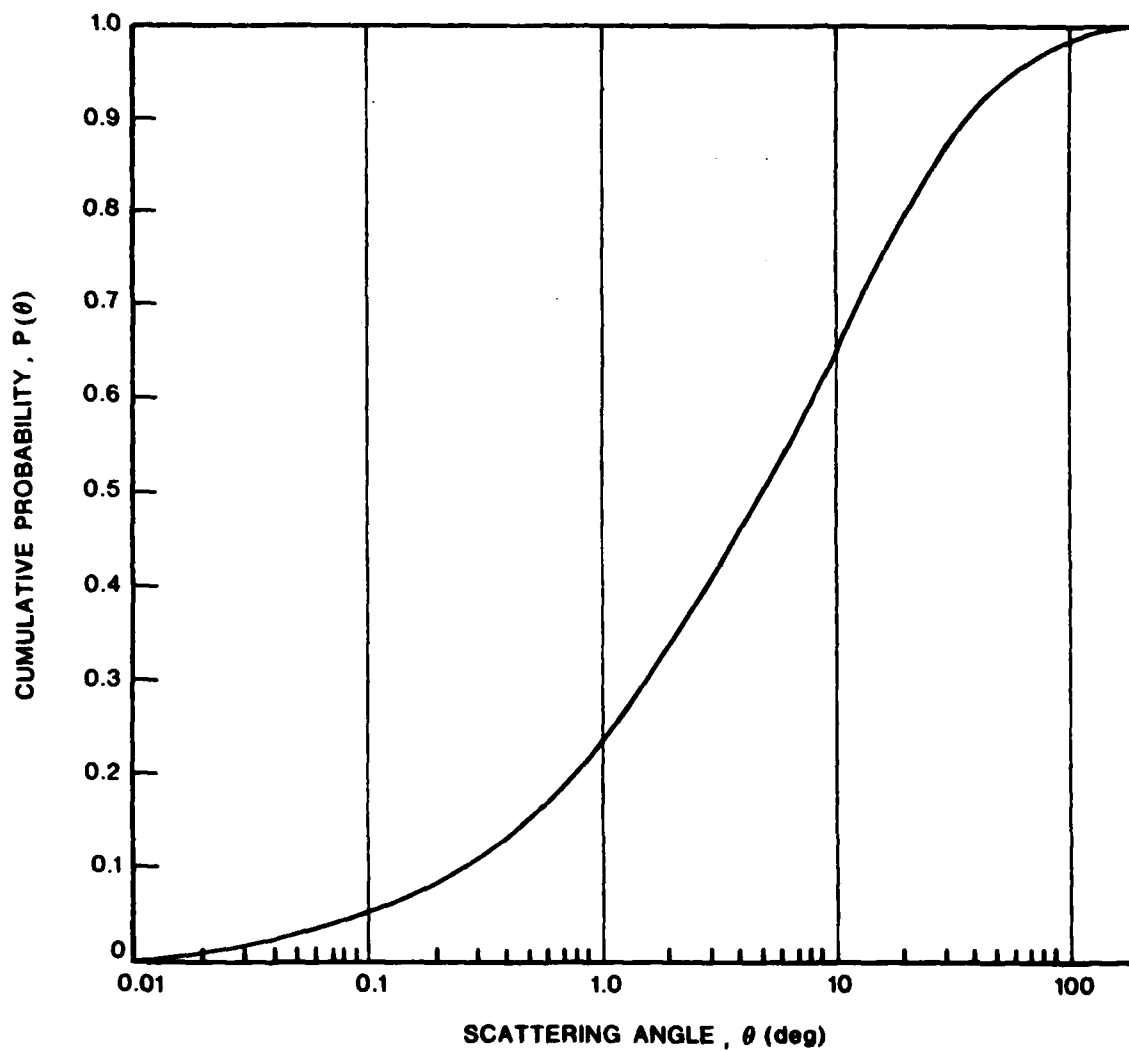


Figure 7. Cumulative probability function derived for the value  $b = 1.663 \text{ m}^{-1}$

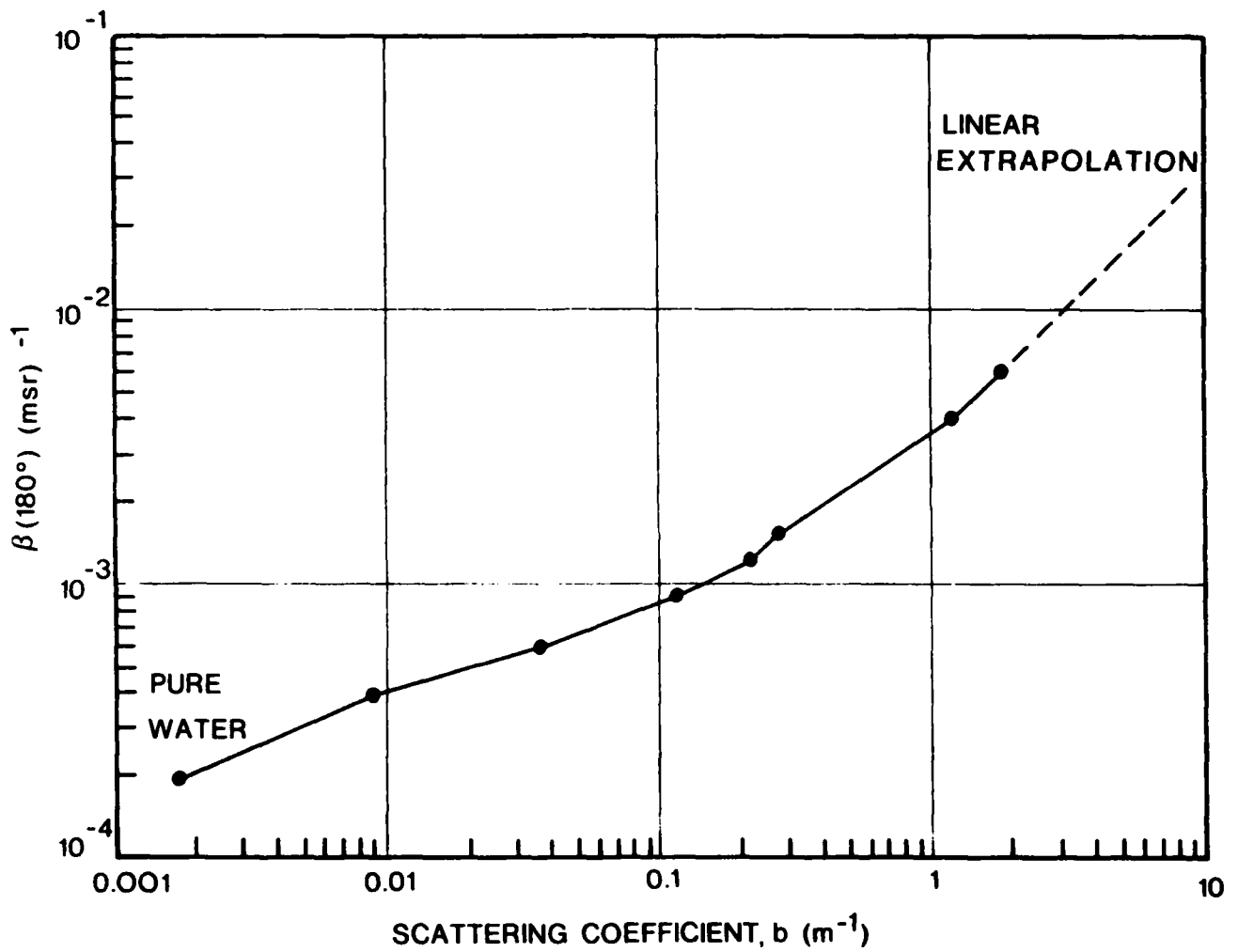


Figure 8. Relationship between values of volume scattering function at  $180^\circ$  and scattering coefficient

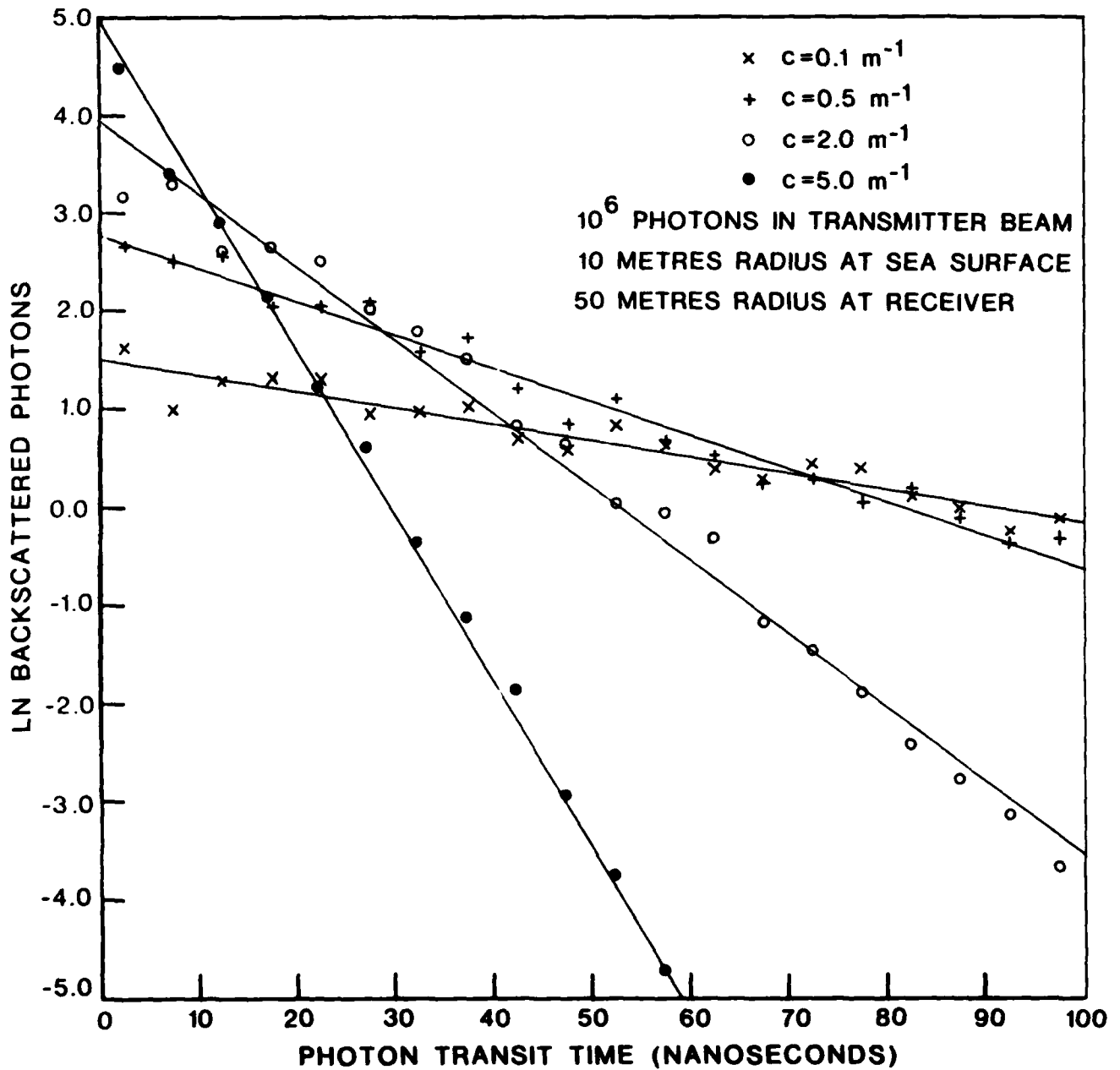


Figure 9. Computed numbers of backscattered photons versus time collected at the airborne receiver

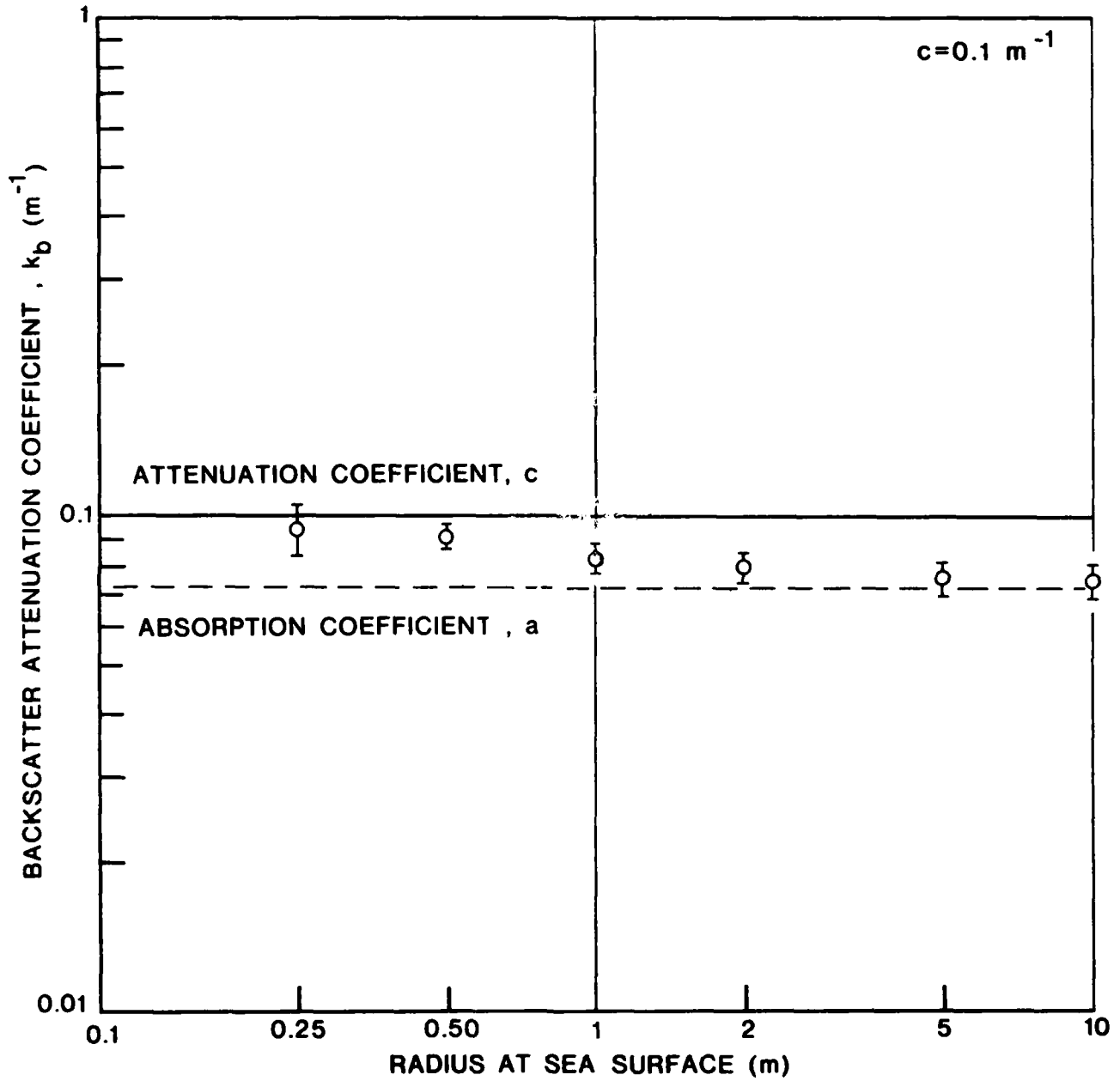


Figure 10. Values of backscatter attenuation coefficient computed for  $c = 0.1 m^{-1}$

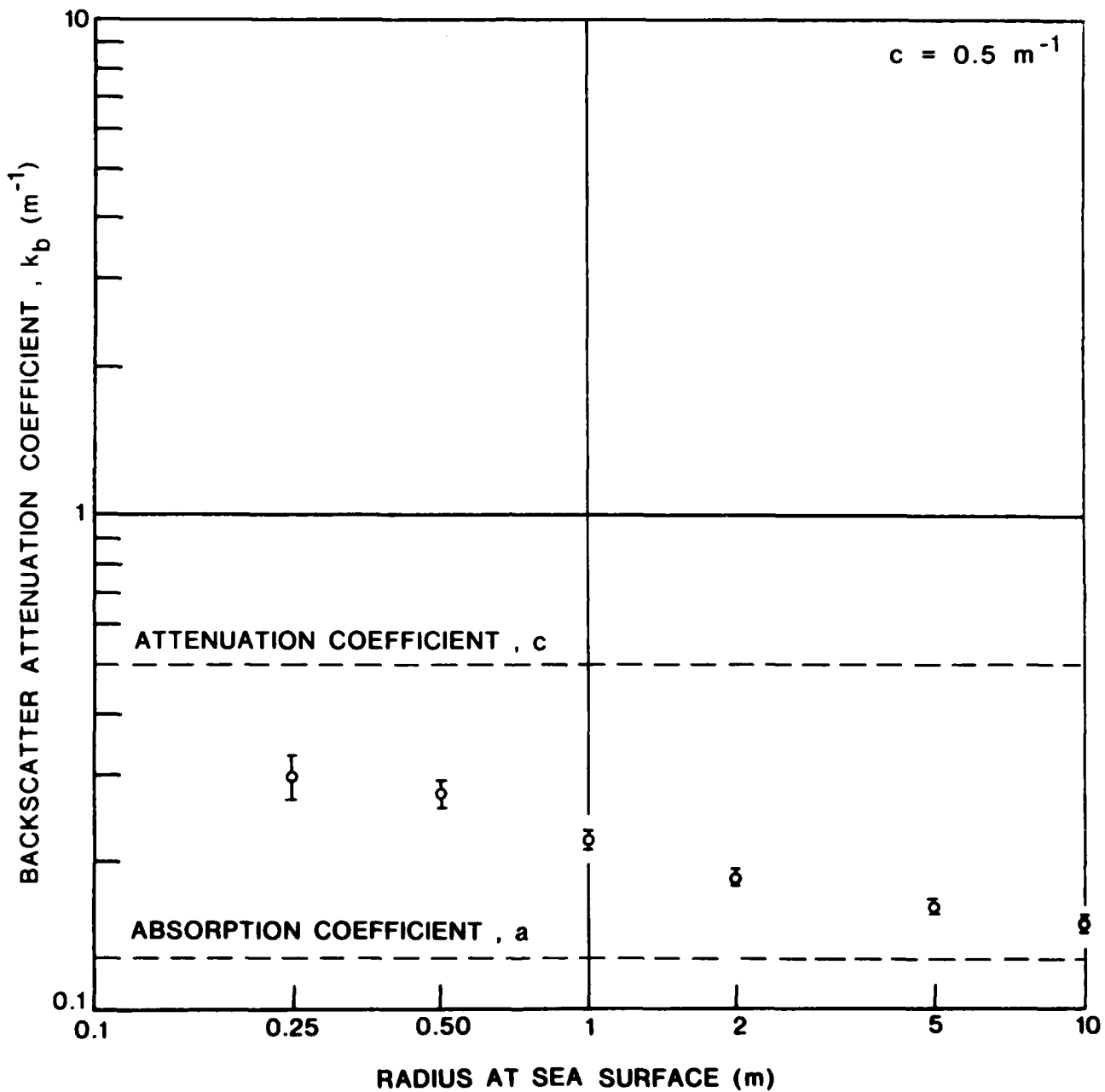


Figure 11. Values of backscatter attenuation coefficient computed for  $c = 0.5 m^{-1}$

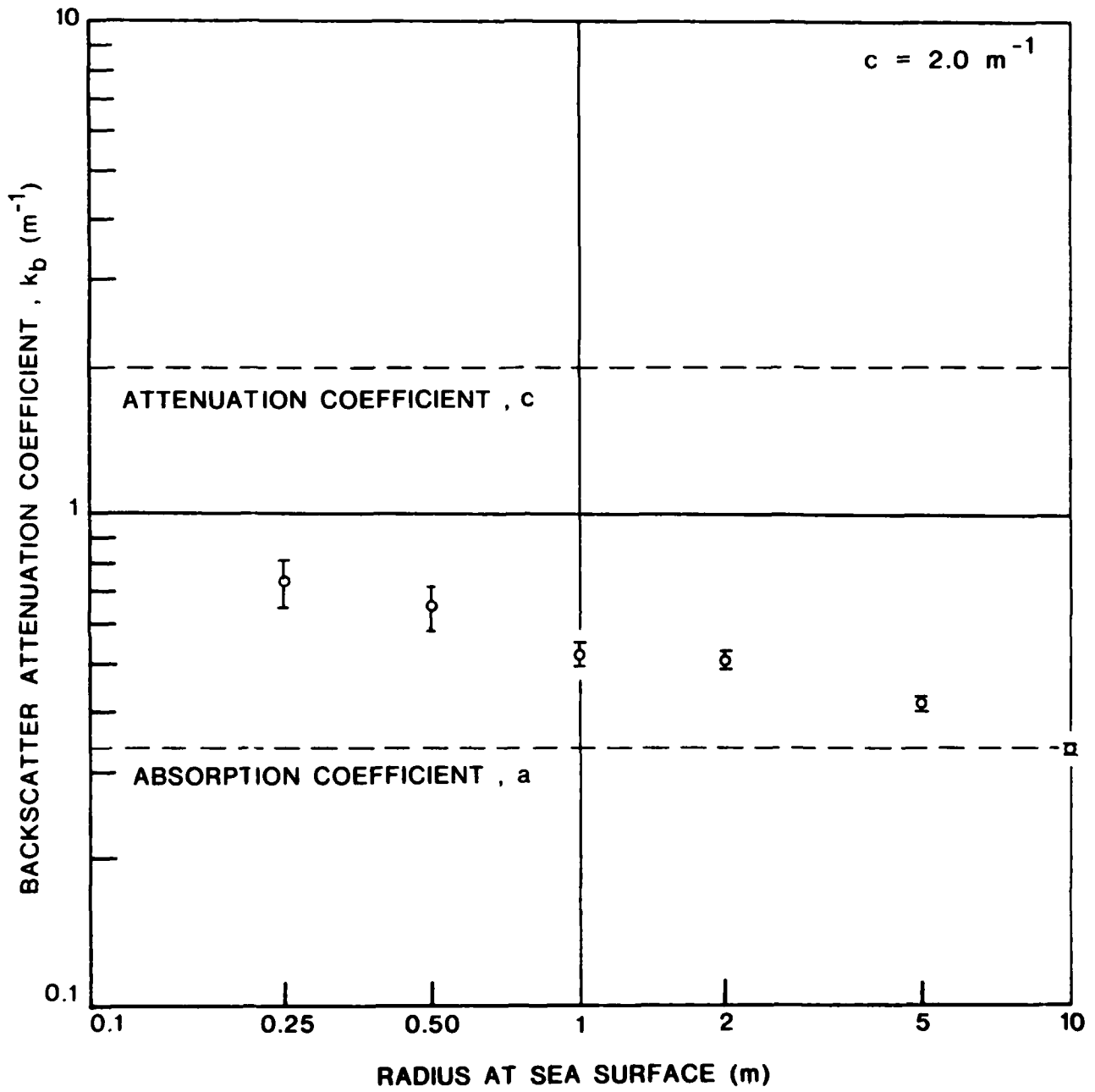


Figure 12. Values of backscatter attenuation coefficient computed for  $c = 2.0 m^{-1}$

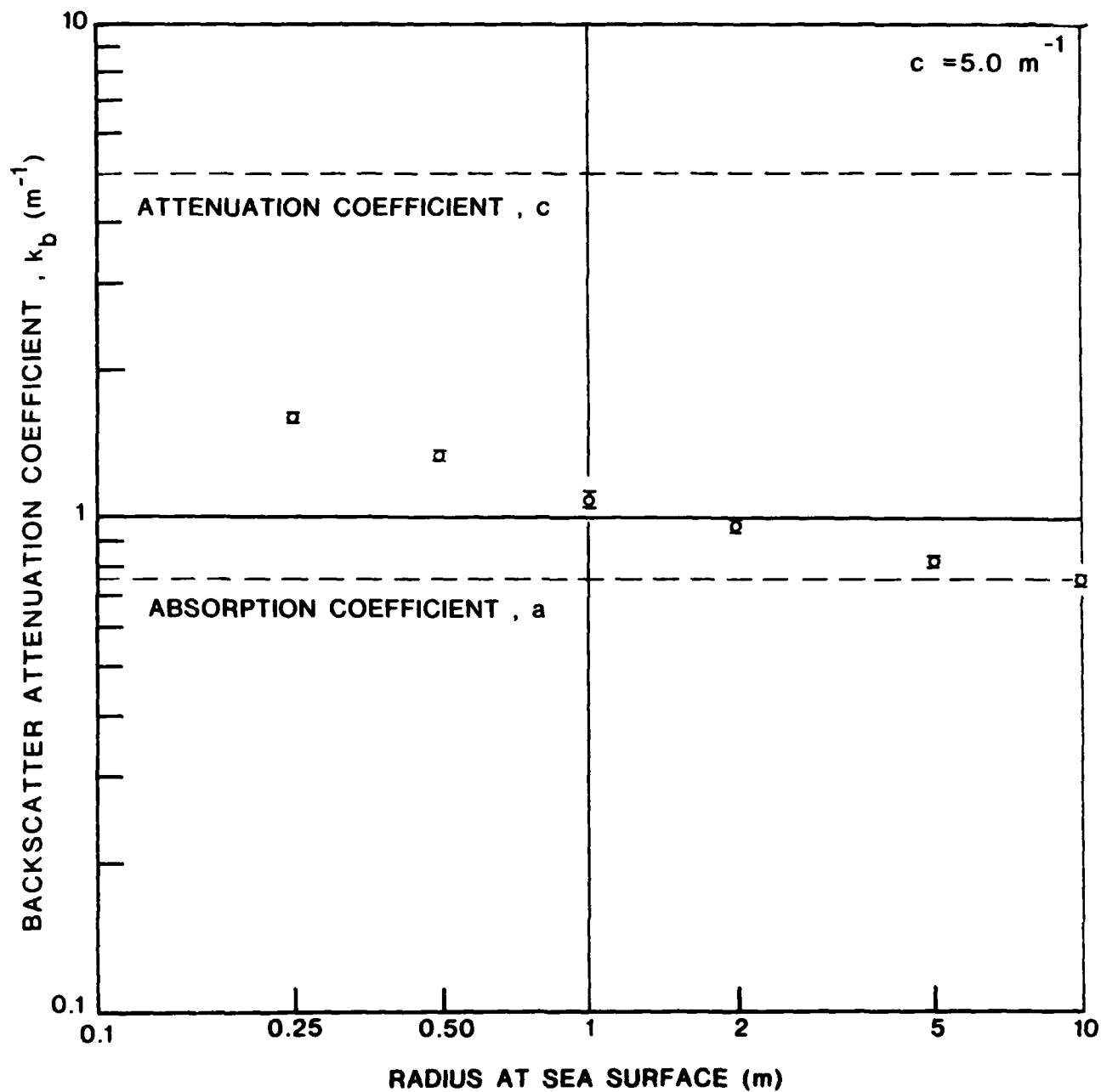


Figure 13. Values of backscatter attenuation coefficient computed for  $c = 5.0 m^{-1}$

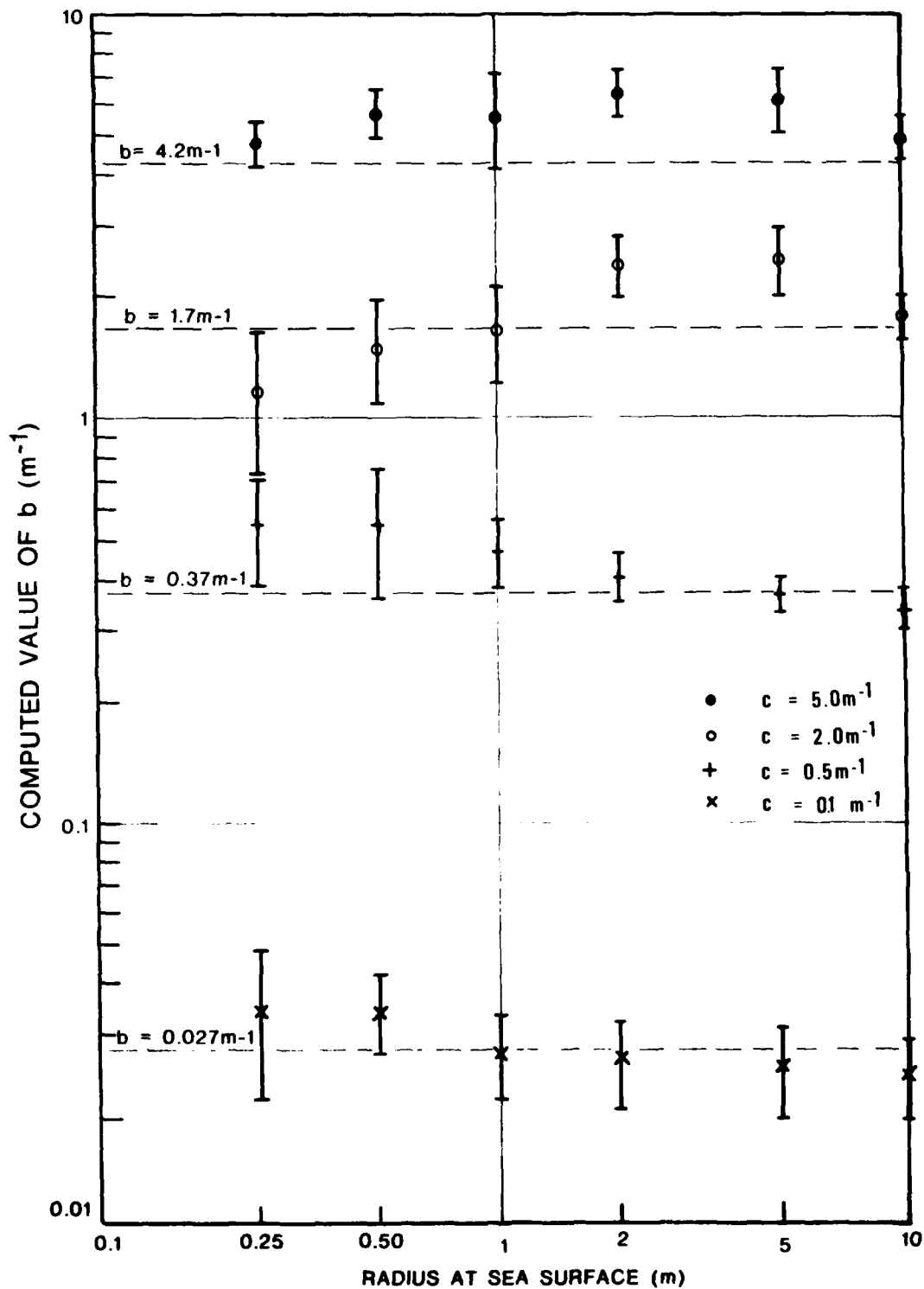


Figure 14. Values of scattering coefficient computed for  $c = 0.1, 0.5, 2.0$  and  $5.0 m^{-1}$

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a EJC Thesaurus Terms	Lasers Monte Carlo method Simulation Backscattering	Sea water Turbidity Light transmission Wave propagation
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16 SUMMARY OR ABSTRACT:  
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A Monte Carlo simulation study of laser backscatter from sea water has been carried out to provide data required to assess the feasibility of measuring inherent optical propagation properties of sea water from an aircraft. The possibility was examined of deriving such information from the backscatter component of the return signals measured by the WRELADS laser airborne depth sounder system. Computations were made for various water turbidity conditions and for different fields of view of the WRELADS receiver. Using a simple model fitted to the computed backscatter data, it was shown that values of the scattering and absorption coefficients can be derived from the initial amplitude and the decay rate of the backscatter envelope.

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