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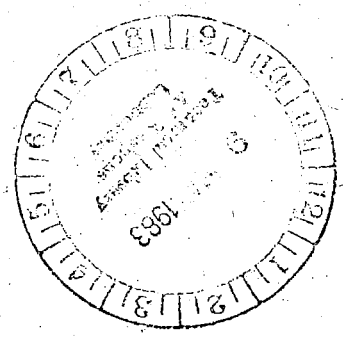

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Measurements of Spectral Attenuation Coefficients in the Lower Chesapeake Bay

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INTRODUCTION

The transmission of light through seawater is an important and frequently studied parameter in oceanography. It is of interest for several reasons, including measurements of underwater visibility, photosynthesis rates, sediment transport, and chemical composition. A recent interest in determination of oceanographic properties by remote sensing has intensified the requirement for the basic optical properties of seawater. For example, at a 1973 conference devoted entirely to hydrographic measurements by remote laser sensing (ref. 1), experiments were described for determination of phytoplankton concentration, water depth, temperature, salinity, sediment transport, dissolved organic matter, and oil pollution. In almost all these experiments, the transmission of the water is required for calibration or determination of the limits of measurement.

For the clear waters of the open sea, abundant data are available for transmission, absorption, and scattering at various wavelengths. In estuarine waters these optical properties are not nearly so well-known, mainly because the optical properties of a given estuary can change markedly with time. In the Chesapeake Bay such measurements can be expected to change by several hundred percent from day to day or week to week. Likewise, at a given time, the variations with position may be of similar magnitude.

From recent reports concerning estuarine optics it has become evident that incorrect values are being used for the spectral attenuation coefficient. The widely accepted measurement of spectral attenuation for the Chesapeake Bay was performed in 1944 by Hulburt for a single sample taken near Bloody Point in the upper Bay. (See ref. 2.) These data, which are shown in figure 1, appear in almost all texts concerning optical oceanography and have been used in many recent papers in which "Chesapeake Bay transmission" is required to support a calculation. To illustrate the inadequacy of these data, the data of reference 2 were compared with recent transmissometer studies made in the lower Bay by the Institute of Oceanography at Old Dominion University, Norfolk, Virginia. (See ref. 3.) Measurements in the blue-green spectral region resulted in beam attenuation coefficients from 2.8 m^{-1} to 5.3 m^{-1} over a transect between the Virginia Capes. Hulburt's data over the same wavelength range are about 0.35 m^{-1}, or a factor of 10, lower than the data observed in the present study. Furthermore, in a study made in 1951, Burt (ref. 4) observed attenuations consistent with fairly clear water in the upper Bay ($c \approx 0.7$ m^{-1} at the mouth of the Potomac River) and with turbid water in the lower Bay ($c \approx 4.5$ m^{-1} at the entrance to the James River).

The previous discussion serves to point out the lack of knowledge about the optical-attenuation properties of estuaries in general, and of the Chesapeake Bay in particular. The problem has two salient features:

(1) Marked variations of attenuation coefficients with space and time may be expected.

(2) The accepted values are too small by as much as an order of magnitude.

The purpose of this experiment was to measure spectral attenuation coefficients at several locations in the lower Chesapeake Bay over a time period of several months

and over a wavelength range from 3500 to 8000 Å. Measurements were made on both filtered and unfiltered water samples in order to separate effects due to suspended and dissolved materials.

SYMBOLS

a	absorption coefficient, m^{-1}
$\bar{a}$	average absorption coefficient, m^{-1}
a'	absorption coefficient for filtered sample, m^{-1}
a_d	absorption coefficient for dissolved organic matter (DOM), m^{-1}
a_p	absorption coefficient for particles, m^{-1}
a_w	absorption coefficient for water, m^{-1}
b	scattering coefficient, m^{-1}
b_f	scattering coefficient within field of view (FOV), m^{-1}
b_p	scattering coefficient for particles, m^{-1}
b_w	scattering coefficient for water, m^{-1}
c	beam attenuation coefficient, m^{-1}
c_p	beam attenuation coefficient for particles, m^{-1}
F	light flux, W
i	current produced by photomultiplier
L	attenuation cell path length, m
n	index of refraction
R	Fresnel reflection coefficient
T	transmittance
T_m	measured transmittance
T_W	transmittance of cell windows
X	distance along cell path, m
$\beta(\theta)$	scattering function, m^{-1}-sr^{-1}
Δ	increment
δ	ratio of scattering coefficient within FOV to total scattering coefficient

θ scattering angle, deg

Abbreviations:

DOM dissolved organic matter

FOV field of view, defined on half-angle, deg

UV ultraviolet

EXPERIMENTAL PROCEDURE

The beam transmittance is given by the exponential decay law

$$T = \exp(-cL) \tag{1}$$

where

c attenuation coefficient, m^{-1}

L attenuation cell path length, m

The beam attenuation coefficient c is the sum of two basic contributions: the absorption coefficient a and the volume scattering coefficient b. Absorption a describes the light loss due to internal heating of the medium, and b describes the loss due to scattering out the light beam. In turn,

$$a = a_w + a_d + a_p \tag{2}$$

$$b = b_w + b_p \tag{3}$$

where

a_w absorption coefficient for pure water, m^{-1}

a_d absorption coefficient for dissolved organic matter (DOM), m^{-1}

a_p absorption coefficient for particles, m^{-1}

b_w scattering coefficient for water (Rayleigh scattering), m^{-1}

b_p scattering coefficient for particles (Mie scattering), m^{-1}

The two measurements described in this paper are

$$c = a + b \tag{4}$$

for an unfiltered sample and

$$a' = a_w + a_d + b_w \tag{5}$$

for a filtered sample. Here, b_w is small compared with $a_w + a_d$ and may be neglected. (See ref. 5.) Furthermore, since a_w is known from previous work (refs. 6 through 10), a_d, due to dissolved organic matter (DOM) which is also known as Gelbstoff, can be estimated by

$$a_d = a' - a_w \tag{6}$$

The attenuation by particles can also be deduced from the measurements by

$$c_p = a_p + b_p = c - a' \tag{7}$$

Beam transmittance is measured by recording the reduction in intensity of a parallel beam of light after passing through a given distance of water. Figure 2 shows a schematic diagram of the optical layout of a typical transmissometer. Light from a small source is collimated, limited by an aperture stop, and passed through the sample cell to a bandpass filter and detector. Several apertures between the cell and detector limit the field of view for rejection of scattered light. To measure transmittance, the cell is moved out of the beam to record initial intensity and then is moved into the beam to record the attenuated intensity. Several possible sources of systematic error in this measurement are given as follows:

(1) Energy-density changes in the light beam and shift of the image because of the thickness of the cell

(2) Stray light in the bandpass filter

(3) Reflection losses at the cell windows

(4) Inclusion of forward scattered light in the receiver field of view (FOV)

The thickness of the cell will cause a shift in the focal plane if the light beam is not well collimated and will displace the image laterally if the cell windows are not parallel. This possibility was controlled by alignment until no difference could be observed in the beam size and image position with or without the cell.

Stray light was eliminated by the use of a high-quality monochromator as the bandpass filter and the inclusion of auxillary blocking filters in front of the entrance slit.

Reflection losses at the cell windows were corrected by calculating the reflectance at each interface by using the Fresnel formula

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \tag{8}$$

where n_1 and n_2 are the indices of refraction on each side of an interface. (See ref. 11.) Table I shows details of the calculation. The effective transmittance of the water sample is

$$T_{true} = \frac{T_m}{0.92} \tag{9}$$

The apparatus used for measurement of beam transmittance in this experiment is shown schematically in figure 3. The source was a 75-W "point" arc lamp filled with xenon. The lamp produces a strong continuum from 3000 Å to above 10 000 Å from a volume approximately 0.038 cm in diameter. The light from the source was rendered parallel by a 2.54-cm-diameter quartz lens of focal length 20.3 cm. An aperture stopped the beam down to a 1.2-cm diameter. The sample cell was machined from aluminum to have an inside diameter of 5.08 cm and was black anodized for corrosion resistance and minimum reflection. The ends were fitted with optically flat, UV-grade quartz windows which could be easily removed for cleaning. The inside distance between windows was 25.4 cm. The cell was mounted on rails so that it could be moved in and out of the light beam with good precision. A filter holder was used to hold neutral-density filters for adjustment of the light level and color filters to help in reduction of stray light. The monochromator was a 1/3-m Czerny-Turner type with an S-20 photomultiplier detector. The output signal was measured with an ammeter having a variable full-scale sensitivity.

Initial measurements were made by using pure water in the cell to determine if the errors due to cell thickness, stray light, and window reflections had been minimized. In the absence of particulates, beam attenuation closely approximates absorption so that attenuation measurements in this paper can be compared with previously reported data for absorption by pure water. (See refs. 6 through 10.) This comparison is shown in figure 4. The present data compare well over the entire range of wavelength, and especially well at wavelengths above 6000 Å. For the relatively short cell-path length, the measurement is more accurate for the attenuation characteristic of these wavelengths. (See appendix A.) There is also less chance of absorption by dissolved impurities at these wavelengths than at the lower wavelengths. These measurements on pure water indicated that errors from the sources described previously had been minimized.

The absorption data for pure water (fig. 4) illustrated how deceptively difficult attenuation measurements can be. Control of the error sources results in a trade-off problem because of the interaction of the errors. For example, limiting the field of view to exclude forward scattering light requires a reduced-entrance aperture to the receiver and, consequently, a weaker and more noisy signal. Use of longer cells for wavelengths of weaker absorption (see fig. A2 in appendix A) increases the possibility of distortion of the transmitted beam. The preparation of pure water, free of traces of DOM and particles, is a well-known difficulty. (See ref. 5, ch. 3.) This is particularly true in the UV where scattering and DOM absorption increase with decreasing wavelength. Therefore, the scatter in data shown in figure 4 is not unexpected and illustrates the present state of knowledge of water absorption.

Forward scattering can generally be neglected if the FOV is restricted to less than 1°. (See ref. 5, ch. 3.) This error is discussed in appendix B for typical optical constants where it can be seen that an FOV less than 0.2° should be chosen to achieve errors below 5 percent. The exclusion of forward scattered light was accomplished by a judicious use of apertures to minimize the FOV. As shown in appendix B,

for the FOV of the present apparatus (0.13°), the resulting error in the measured attenuation coefficient should be less than 3 percent. Note that this is not a random error but is a systematic 3-percent underestimation. Since a/b is not known, an actual correction cannot be made. As a check for scattered light in the FOV, a water sample with $c \approx 7\ m^{-1}$ was measured with both a 0.2° FOV and a 0.1° FOV, the reduction being accomplished by reducing the slit height by a factor of 2. No difference could be observed in the measured transmission. As described in appendix A, the random error in this experiment is about 5 percent. The systematic error appears to be buried in the random error.

The water samples were filtered with standard Gelman filters and filtering apparatus. The filter funnel was a Parabella type for 47-mm-diameter filter pads. A combination of two filters was used which consisted of a 0.3-μm fiberglass prefilter over a 1.2-μm membrane filter. The former removes 99 percent of particles larger than 0.3 μm, and the latter has a pore diameter of 1.2 μm. To achieve repeatability, the following fixed precedure was used for all samples: (1) The funnel was rinsed with water from the sample jar; (2) a sample of 100 mL was filtered and used to rinse the collecting flask; and (3) a sufficient amount of sample was filtered to rinse and fill the sample cell.

All samples were acquired by the rope-and-bucket technique and were stored in widemouth polyethelene containers. Preservatives were not added, but the samples were chilled and removed from light until attenuation measurements were made. Measurements were performed within 2 hr after collection for the pier samples and within 8 hr for the shipboard samples.

RESULTS AND DISCUSSION

Sample collection was undertaken on a weekly basis during the fall of 1974 at the U.S. Coast Guard Reserve Training Center in Yorktown, Virginia. On some days samples were also taken at Newport News Point on the north side of Hampton Roads. A number of samples were taken in the lower Chesapeake Bay and seaward to the Chesapeake Light Tower during cruises of the R.V. Linwood Holton during 1975 and 1976. For comparison, several samples were taken in the James River near Jamestown at the approximate limit of the salt-water/fresh-water interface and just beyond the Bay mouth in "coastal water." All sample sites are shown on the map in figure 5.

Table II shows the numbering of each sample along with location, date, temperature, and salinity. Table III shows the measured attenuation coefficients for the unfiltered samples, and Table IV shows the measured absorption coefficients for filtered samples.

The attenuation coefficients are shown graphically in figure 6 for six samples representative of the total data. The transition from curve to curve is well-behaved with no abrupt changes in the relative spectral shapes. The attenuation coefficients displayed indicate the range of values to be expected in the lower Chesapeake Bay. The lowest curve, sample 12, is representative of clear conditions when land runoff, plankton blooms, and bottom agitation are minimal. The upper curve can be exceeded when the sediment input from the river increases following heavy rains and when strong local winds cause bottom scouring. Examples of the attenuation coefficients during these more turbid conditions are shown in figure 7. It should be emphasized that figure 6 represents a typical variation and figure 7 represents the extremes that can be obtained under the special conditions indicated.

As a check on sample deterioration with time, the attenuation coefficients of several samples were determined first within 30 min after collection and again 12 hr later. The deterioration between the two times was within a few percent. Reexamination after 3 days, however, yielded a significant difference as shown in figure 8. Note that the absorption coefficient did not change significantly.

The possible problem of a change in the optical properties between the time of collection and measurement was found to be insignificant for intervals of less than 12 hr. The only precautions taken were to transport all samples in an ice chest for chilling and removal from light. The attenuation coefficients did change after storage for 3 days in the ambient conditions of the laboratory. It was obvious by visual inspection that large "flakey" particles had formed and settled on the bottom of the sample jar. After shaking the samples the attenuation coefficients were still far less than those originally measured as shown in figure 8. At the same time, however, the change in the absorption coefficient was negligible. The effects of longer sample storage time are formation of larger particles, probably by agglomeration, and a decrease in attenuation. Whatever biological and chemical decay occurred did not result in additional DOM detectable by absorption.

The spectral absorption coefficients are noticeably similar, particularly where the salinities are about equal. For this reason, the decision was made to average the coefficients at each wavelength and to calculate the standard deviation as an indicator of variability. Samples 15 and 16 were excluded from the averaging since they came from fresher water where greater absorption due to DOM might be expected. The salinities for samples 1 and 2 were not measured; but from repeated studies, values between 20 and 22 parts per thousand (ppt) have been observed at these locations. The average and the standard deviation are shown in figure 9. The pure water absorption and the attenuation data of Hulburt (ref. 2) have been included for comparison. The absorption coefficients shown in figure 9 indicate practically no variation, particularly if the fresher water sites, samples 15 and 16, are excluded. Note that for the fresher water, the absorption at shorter wavelengths increased with decreasing salinity. These features have been observed previously (ref. 12) and are attributable to a land-derived source of DOM with subsequent linear mixing of fresh and salt water. Figure 10 shows the spectral absorption coefficients for DOM in the lower Chesapeake Bay, which were obtained by substracting the absorption due to pure water from the data of table IV. Data obtained in the open ocean (ref. 5) have been included to indicate how DOM maintains its spectral characteristics upon subsequent dilution.

The attenuation for particles was obtained by subtracting the absorption coefficient from the corresponding attenuation coefficient as shown in figure 11. This figure illustrates both the dominance of attenuation by particles and the characteristic monotonic increase of the attenuation with decreasing wavelength.

CONCLUDING REMARKS

The spectral attenuation measured by Hulburt in 1944 is still widely used in the literature for "Chesapeake Bay attenuation." The attenuation for Bay water in 1944 was about the same as the present-day absorption for filtered Bay water. It is tempting to conclude that the difference is due to increased sediment loading over the years. Although this may contribute in part, there is an additional consideration, that of geographic location. Hulburt's data were taken from a single sample obtained off Bloody Point in the upper Bay. In an intermediate time frame, Burt

observed attenuation coefficients of about 0.7 m^{-1} in the upper Bay and about 4.5 m^{-1} in the lower Bay. The point to be made here is that because of both temporal and spatial variability, the attenuation for a given Chesapeake Bay sample can vary between the almost "swimming-pool" clarity observed by Hulburt to the muddy-river turbidity of sample 25 in this paper. Presented are both the range to be expected in the absence of storms or heavy spring discharge and the extremes which may be obtained.

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APPENDIX A

ERROR DUE TO READOUT

The random error of the laboratory measurement of transmittance is limited by the precision of reading the ammeter. The readout is by means of an analog scale graduated from 0 to 100 in increments of 1. The overall system noise, which includes fluctuations of the background lamp, photomultiplier dark current, and amplifier noise, is very slight, generally less than ±1/4-scale division. The error for a given scale reading is assumed to be ±1.

The measured transmittance is given by

$$T_m = T_W \exp(-cL) = i/i_0 \tag{A1}$$

where

T_W transmittance of cell windows

i_0 signal current without cell

i signal current with cell

The root-mean-square error of T_m in terms of the fractional standard deviation for a quotient (ref. 15) is

$$\frac{\Delta T_m}{T_m} = \left[\left(\frac{\Delta i}{i}\right)^2 + \left(\frac{\Delta i_0}{i_0}\right)^2\right]^{1/2} \tag{A2}$$

where Δi and Δi_0 are both 1. The current i_0 was always adjusted to 100 so that $T = 0.01 \times i$. Thus, equation (A2) becomes

$$\frac{\Delta T}{T_m} = \left[\left(\frac{1}{100T_m}\right)^2 + \left(\frac{1}{100}\right)^2\right]^{1/2} = \frac{1}{100T_m}\left(T_m^2 + 1\right)^{1/2} \tag{A3}$$

The error in calculating c from T_m is given by differentiating equation (A1). Thus,

$$\Delta T_m = T_W \exp(-cL)(-L\ \Delta c) = -LT\ \Delta c \tag{A4}$$

Solving equation (A1) for c gives

$$c = -\frac{1}{L}\ln\left(T_m/T_W\right) \tag{A5}$$

Combining equations (A3), (A4), and (A5) gives

$$\frac{\Delta c}{c} = \frac{1}{\ln\left(T_m/T_W\right)}\frac{\Delta T_m}{T_m} = \frac{1}{\ln\left(T_m/T_W\right)}\frac{\left(T_m^2 + 1\right)^{1/2}}{100T_m} \tag{A6}$$

APPENDIX A

The quantity $\Delta c/c \times 100$ yields the familiar percent error for the measurement of c. Figure A1 shows this error for the 0.254-m cell used. Over the range of c expected for the Chesapeake Bay, this cell length gives a nominal 5-percent error. Figure A2 shows the error for other cell lengths to indicate optimum lengths for various attenuations. A similar treatment of the readout error has been described by Austin in reference 16.

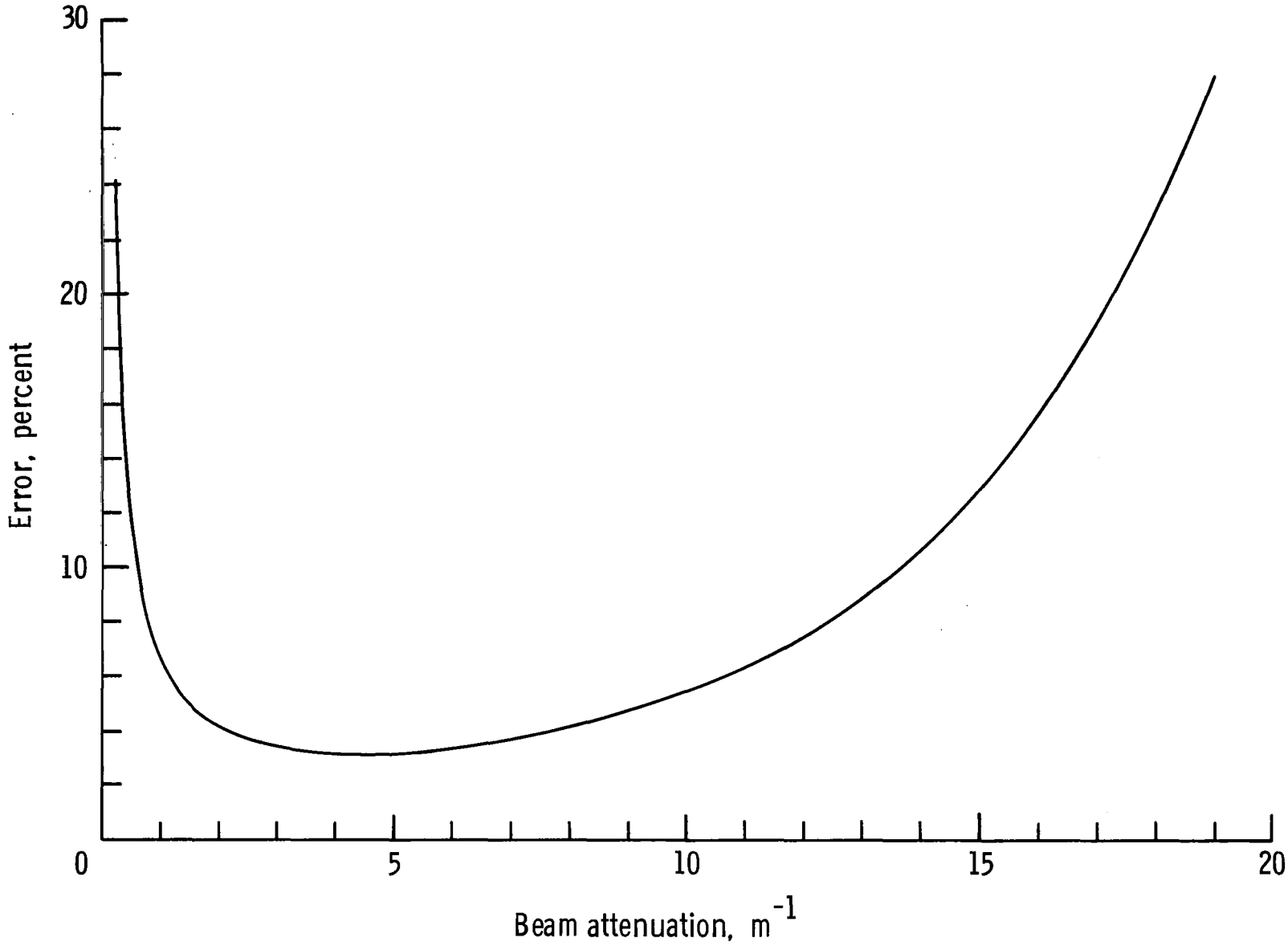

Figure A1.- Readout error for 0.254-m cell for 1-percent-scale precision.

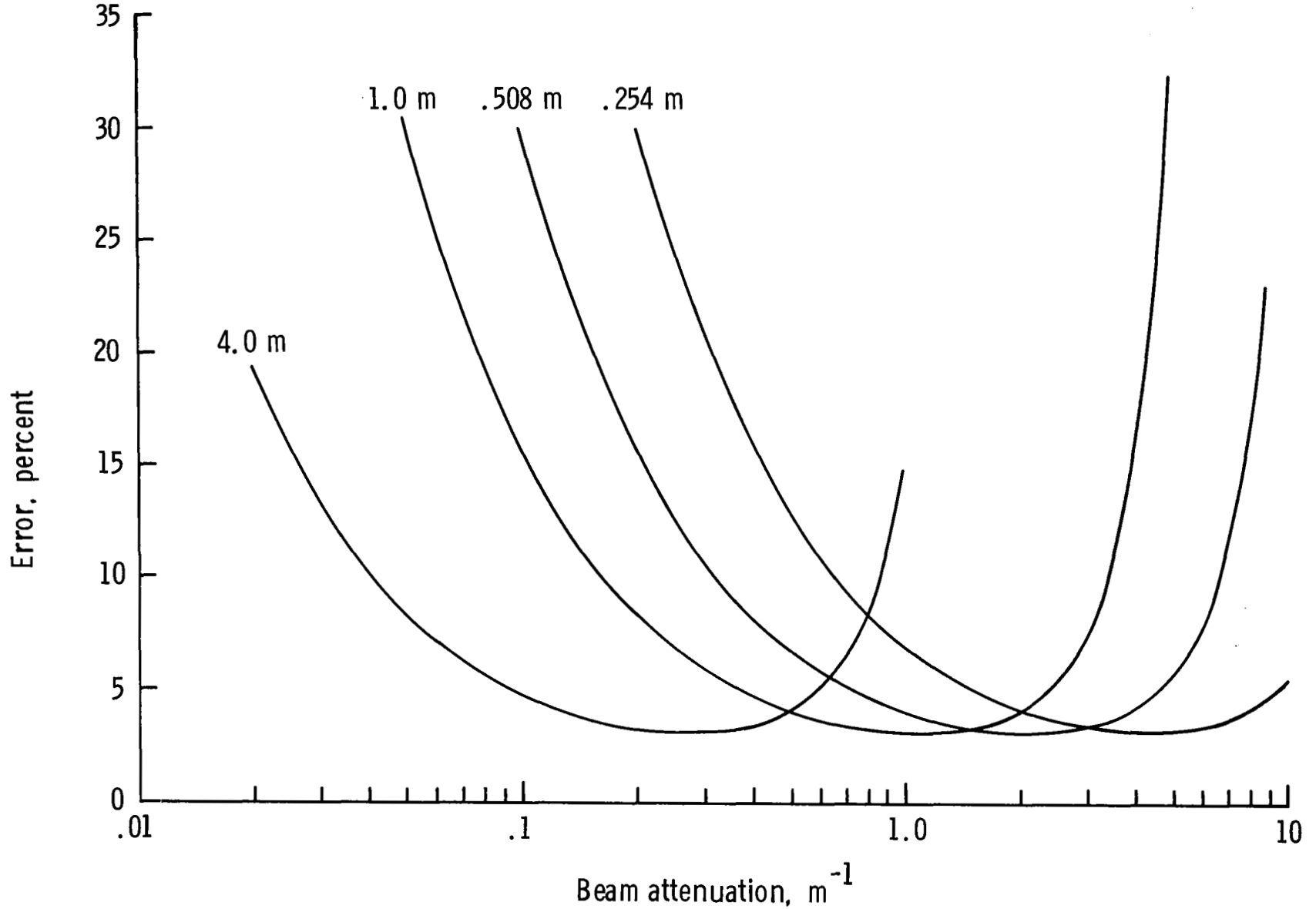

Figure A2.- Readout error for other cells for 1-percent-scale precision.

APPENDIX B

ERROR DUE TO FORWARD SCATTERED LIGHT

Measurement of the attenuation coefficient requires that no scattering event be collected by the receiver. However, because of the finite FOV, some forward scattered light does enter the receiver optics. The amount of error that this causes can be estimated by knowing the receiver FOV, absorption and scattering coefficients, and the scattering function.

The change is flux in a beam of light passing through a scattering and absorbing medium of thickness ΔX and is given by

$$\Delta F = -cF\ \Delta X = -(a + b)F\ \Delta X \tag{B1}$$

where b is defined in terms of the scattering function $\beta(\theta)$ (ref. 5) by

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin \theta\ d\theta \tag{B2}$$

To account for the scattered light which remains within the receiver FOV, it is convenient to write equation (B2) as

$$b = 2\pi \int_0^{\theta_{FOV}} \beta(\theta) \sin \theta\ d\theta + 2\pi \int_{\theta_{FOV}}^{\pi} \beta(\theta) \sin \theta\ d\theta \tag{B3}$$

$$b = b_f + b' \tag{B4}$$

where b' describes the true loss due to scattering and b_f describes the scattering not resulting in loss. In terms of measured flux, ΔF_m, equation (B1) becomes

$$\Delta F_m = -aF_m\ \Delta X - b'F_m\ \Delta X \tag{B5}$$

$$\Delta F_m = -cF_m\ \Delta X + b_f F_m\ \Delta X \tag{B6}$$

Integrating equation (B6) over $X = 0$ to $X = L$ with the initial condition $F = F_0$ at $X = 0$ gives

$$T_m = \exp(-cL)\ \exp(b_f L) \tag{B7}$$

where T_m is the measured transmittance. If the forward scattering within the FOV is small, then equation (B7) reduces to the usual expression (eq. (1) in the text).

Rearranging equation (B7) gives

$$c = \frac{-1}{L} \operatorname{Ln} T_m + b_f \tag{B8}$$

$$c = c_m + b_f \tag{B9}$$

where c_m is the measured attenuation coefficient.

The fractional error in c then is

$$\frac{\Delta c}{c} = \frac{c - c_m}{c} = \frac{b_f}{c} \tag{B10}$$

Letting b_f be a fraction, δ, of b gives

$$b_f = \delta b \tag{B11}$$

Therefore,

$$\frac{\Delta c}{c} = \frac{\delta b}{a + b} \tag{B12}$$

or

$$\frac{\Delta c}{c} = \frac{\delta}{\frac{a}{b} + 1} \tag{B13}$$

where

$$\delta = \frac{2\pi}{b} \int_0^{\theta_{FOV}} \beta(\theta) \sin \theta \, d\theta \tag{B14}$$

If $\beta(\theta)$ is known, then δ may be estimated for the receiver FOV and equation (B13) can be used to plot error curves as a function of the ratio a/b. The scattering function $\beta(\theta)$ has been measured for a number of water types. (See refs. 12, 13, and 14.) It should be noted that there is a remarkable similarity amongst all the curves and, in fact, they can be made to fall close together by multiplication by a constant. To estimate the FOV error, a typical $\beta(\theta)$ curve was chosen and employed to calculate δ by using equation (B14). The curve used was that for the Long Island Sound station described by Morrison in reference 14 (see fig. (B1)), since this station has a scattering coefficient typical of the Chesapeake Bay ($b \approx 2.2\ m^{-1}$) and has good small-angle information.

The δ ratio calculated for a given curve will typify all curves to the extent to which all $\beta(\theta)$ curves are related by a constant. The δ ratios were calculated by numerically integrating equation (B14) for values of FOV of 0.2°, 1°, 2°, 5°,

and 10°. These were then used in equation (B13) to produce the error curves shown in figure B2. The FOV for the apparatus in figure 3 was 0.13°. Therefore, the error in forward scattering light in this paper should be less than 3 percent.

Figure B2 indicates how easily the error in attenuation measurements can get out of hand by not controlling the FOV. A 1° FOV may seem intuitively sufficient but can cause an error of up to 18 percent.

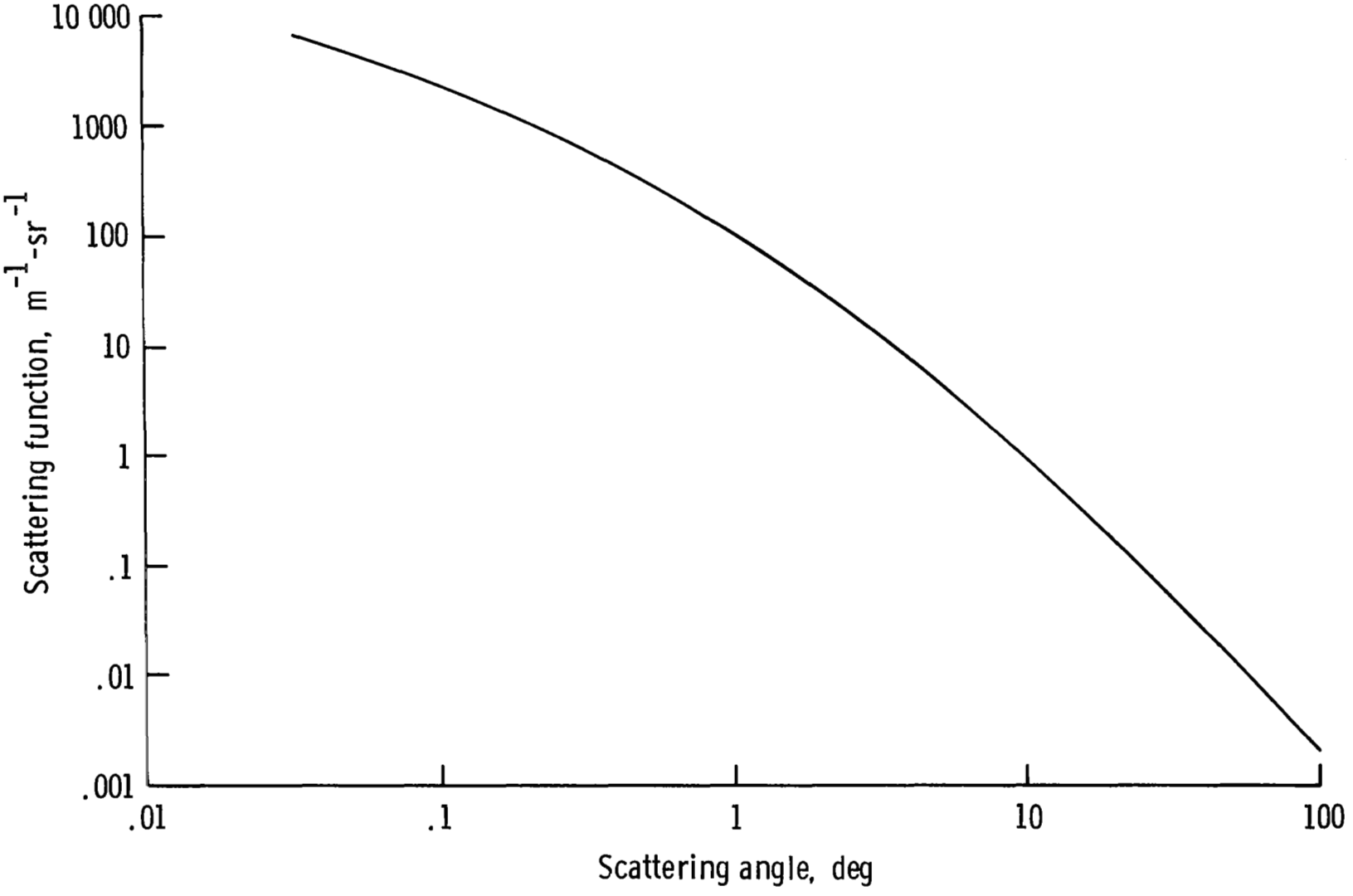

Figure B1.- Data used to estimate FOV error.

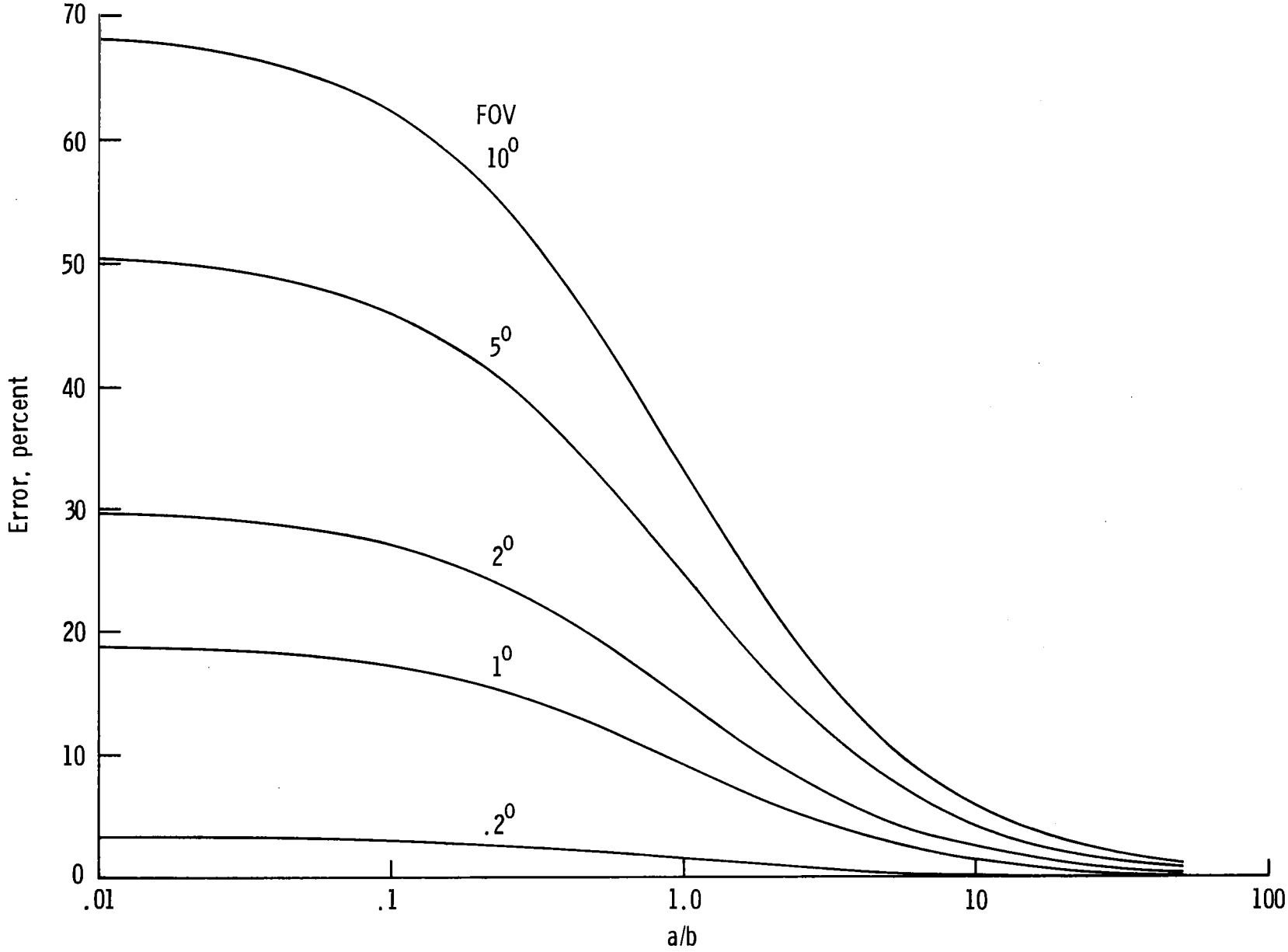

Figure B2.- FOV error.

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TABLE I.- ESTIMATION OF REFLECTION LOSS AT CELL WINDOW

$$\left[R = \left[\frac{(n_Q - n_A)^2}{(n_Q + n_A)^2}\right]^2 \left[\frac{(n_Q - n_W)^2}{(n_Q + n_W)^2}\right]^2\right]$$

Wavelength, Å	Index of refraction n for -			T
	Air (A)	Quartz (Q)	Water (W)	(a)
3600	1.000	1.475	1.348	0.924
5890	1.000	1.458	1.333	.928
7680	1.000	1.454	1.329	.929

$^{a}T = 0.920$ was selected for all calculations since the change with wavelength is small. Rounding to the low side was believed desirable since losses from surface imperfections and internal absorption were not considered.

TABLE II.- DETAILS OF SAMPLE SITES

[Locations are shown in fig. 5.]

Sample	Location (a)	Date	Temperature, °C	Salinity, ppt
1	G	10/1/74		
2	T	10/1/74		
3	Y	10/11/74	17.5	19.9
4	Y	10/18/74	18.7	20.7
5	Y	10/18/74	18.7	20.7
6	N	10/29/74	15.4	21.3
7	Y	10/29/74	15.8	20.9
8	N	11/5/74	17.3	20.6
9	Y	11/5/74	17.6	21.3
10	Y	11/12/74	14.8	22.2
11	Y	11/19/74	11.6	21.6
12	N	11/19/74	11.0	21.3
13	Y	12/6/74	7.0	22.9
14	Y	12/13/74	6.0	23.0
15	W	12/13/74	6.0	13.0
16	J	12/13/74	6.1	1.2
17	H1	7/12/75	26.6	20.6
18	H2	7/12/75	26.2	19.8
19	H3	7/12/75	26.3	22.3
20	H4	7/12/75	26.6	23.6
21	H5	7/12/75	24.3	32.5
22	H6	7/13/75	26.3	22.3
23	H7	7/13/75	25.8	28.7
24	H8	7/13/75	26.8	30.4
25	S	5/11/77	17.3	14.8
26	F	9/19/77		

[a]Locations are designated as follows: Y - USCG, Yorktown; N - Newport News Point; G, T, and H1 to H8 - Lower Bay; W - Warwick River, Newport News; J - Ferry Pier, Jamestown; S - 1 n.mi. west of James River Bridge; F - Fort Monroe.

TABLE III.- MEASURED ATTENUATION COEFFICIENTS FOR UNFILTERED SAMPLES

Sample	Measured attenuation for wavelength of -									
	3500 Å	4000 Å	4500 Å	5000 Å	5500 Å	6000 Å	6500 Å	7000 Å	7500 Å	8000 Å
1	11.1	9.15	8.02	7.27	6.65	6.21	6.00	6.11	7.70	6.77
2	7.86	6.11	5.13	4.68	4.28	4.16	4.16	4.10	6.01	5.21
3	9.15	7.14	6.01	5.46	4.98	4.83	4.41	4.41	6.42	5.37
4	13.5	10.7	9.38	8.74	8.02	7.44	7.14	6.89	8.36	7.56
5	10.7	8.94	7.70	7.01	6.32	6.21	5.91	5.82	7.70	6.65
6	6.42	4.83	4.04	3.48	3.28	3.13	2.99	2.99	5.13	4.28
7	8.74	6.77	5.72	5.13	4.55	4.28	4.10	4.04	6.01	5.13
8	20.4	8.36	7.14	6.53	5.91	5.63	5.37	5.46	7.41	6.32
9	9.15	7.14	6.21	5.63	5.13	4.90	4.68	4.75	6.77	5.72
10	11.5	9.62	8.36	7.70	7.14	6.89	6.42	6.42	8.19	7.27
11	7.41	5.82	4.68	4.22	3.80	3.64	3.48	3.48	5.46	4.68
12	4.98	3.48	2.69	2.32	2.17	2.10	2.03	2.21	4.16	3.43
13	7.70	6.01	4.90	4.28	3.80	3.64	3.48	3.53	5.46	4.75
14	9.15	7.01	5.82	5.21	4.75	4.41	4.22	4.28	6.21	5.37
15	14.2	11.5	9.62	8.36	7.70	7.14	6.77	6.65	8.19	7.41
16	Transmittance less than 1 percent at all wavelengths									
17	8.94	7.14	6.21	5.46	4.98	4.75	4.41	4.55	6.32	5.63
18	9.38	7.41	6.21	5.46	4.83	4.48	4.16	4.16	5.91	5.13
19	10.4	8.74	7.41	6.65	6.01	5.46	5.13	5.05	6.77	6.01
20	8.94	7.27	6.32	5.46	4.90	4.61	4.35	4.28	6.21	5.29
21	1.55	1.08	.804	.701	.650	.752	.804	1.08	3.09	2.48
22	9.38	7.56	6.65	5.82	5.37	4.90	4.75	4.68	6.53	5.63
23	6.65	5.21	4.41	3.92	3.35	3.38	3.18	3.23	5.21	4.35
24	2.28	1.68	1.28	1.08	.938	.965	.965	1.19	3.23	2.60
25			27.0	25.6	23.9	22.0	20.7	20.3	21.1	19.1
26		21.6	18.6	17.1	16.0	15.1	14.3	14.3	16.0	14.1

TABLE IV.- MEASURED ABSORPTION COEFFICIENTS FOR FILTERED SAMPLES

[These samples are the only ones for which a' was determined.]

Sample	Measured absorption, m^{-1}, for wavelength of -									
	3500 Å	4000 Å	4500 Å	5000 Å	5500 Å	6000 Å	6500 Å	7000 Å	7500 Å	8000 Å
1	2.10	1.02	0.550	0.366	0.175	0.358	0.358	0.600	2.73	2.10
2	2.35	1.07	.453	.220	.175	.312	.358	.600	2.73	2.03
3	2.73	1.19	.575	.312	.266	.335	.404	.625	2.82	2.13
4	2.25	1.02	.405	.243	.108	.366	.335	.575	2.73	2.10
5	2.48	1.10	.501	.288	.220	.358	.405	.650	2.82	2.13
6	2.21	1.02	.477	.243	.153	.312	.358	.575	2.73	2.10
7	2.21	.992	.453	.220	.175	.288	.335	.575	2.73	2.13
8	2.25	.965	.477	.266	.197	.312	.358	.625	2.77	2.10
9	2.25	.938	.405	.197	.175	.266	.358	.625	2.82	2.10
10	2.17	.911	.358	.175	.153	.312	.312	.550	2.69	2.10
11	2.73	1.22	.624	.358	.266	.335	.405	.600	2.77	2.10
12	2.44	1.16	.600	.358	.243	.335	.358	.600	2.73	2.10
13	2.44	1.19	.600	.358	.243	.358	.453	.650	2.73	2.13
14	2.64	1.10	.526	.266	.175	.312	.358	.575	2.69	2.10
Average	2.38	1.06	0.500	0.2169	0.195	0.326	0.368	0.600	2.75	2.10
Std. dev.	.208	.099	.082	.060	.047	.029	.037	.029	.044	.025
15	4.04	1.75	0.804	0.501	0.266	0.335	0.405	0.650	2.73	2.10
16	7.70	3.69	1.95	1.19	.752	.701	.650	.726	2.82	2.25

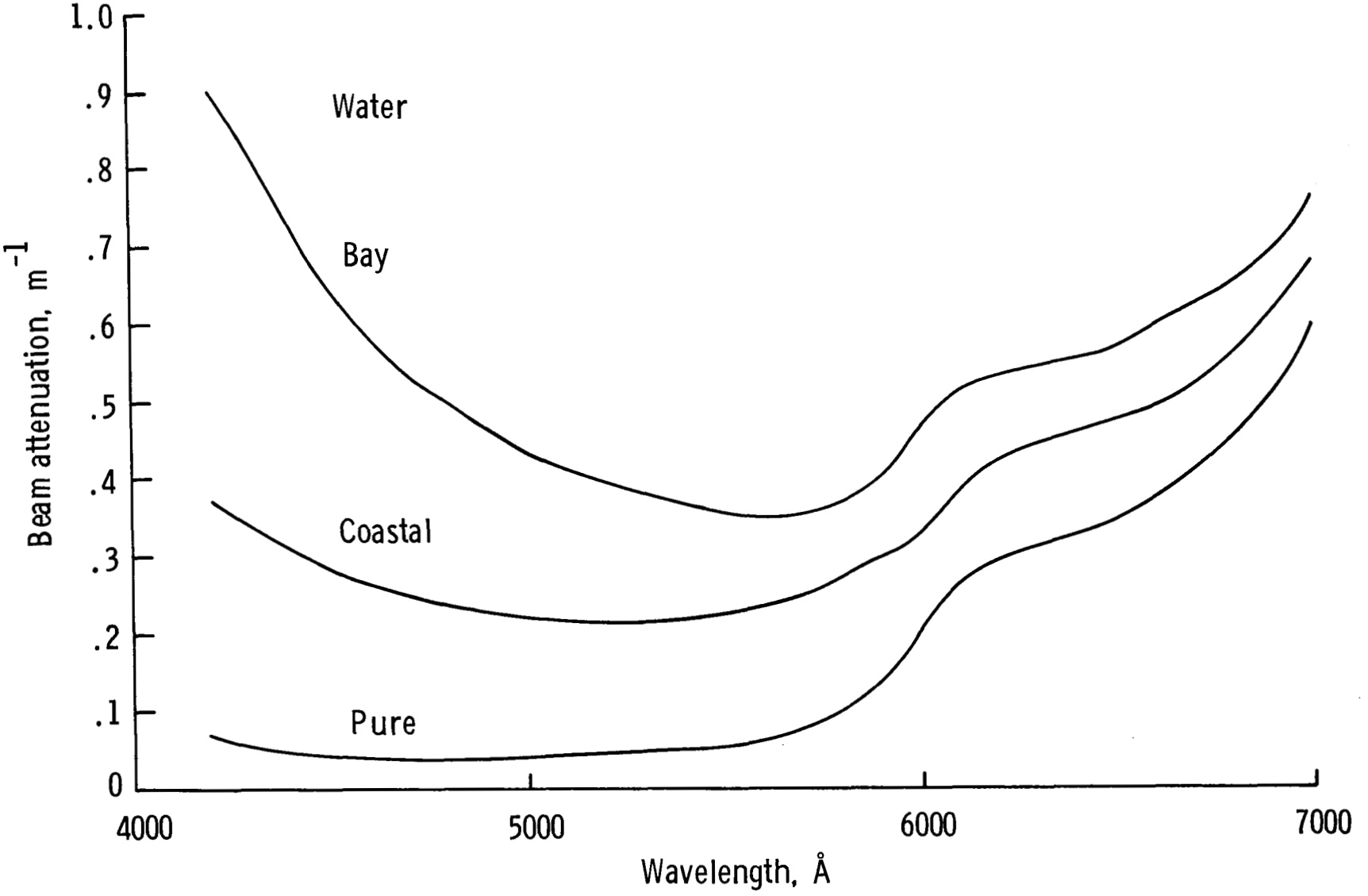

Figure 1.- Hulburt's data. (See ref. 2.)

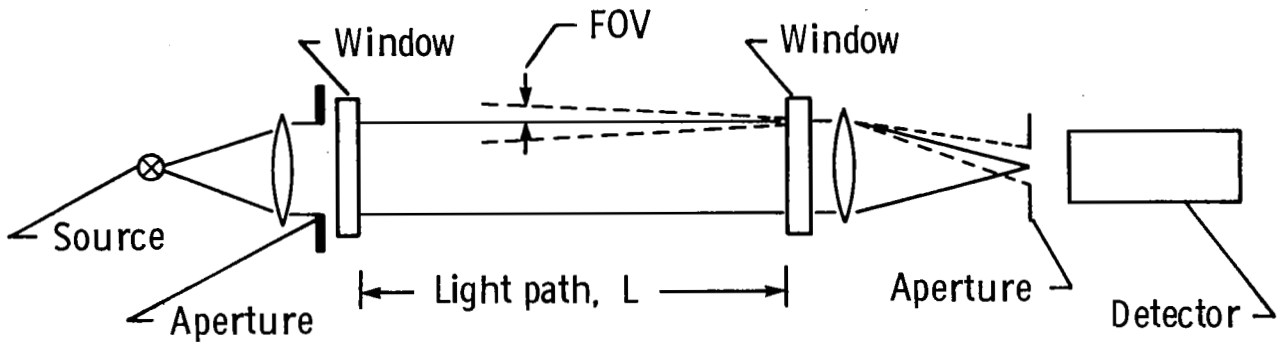

Figure 2.- Beam-transmissometer optics.

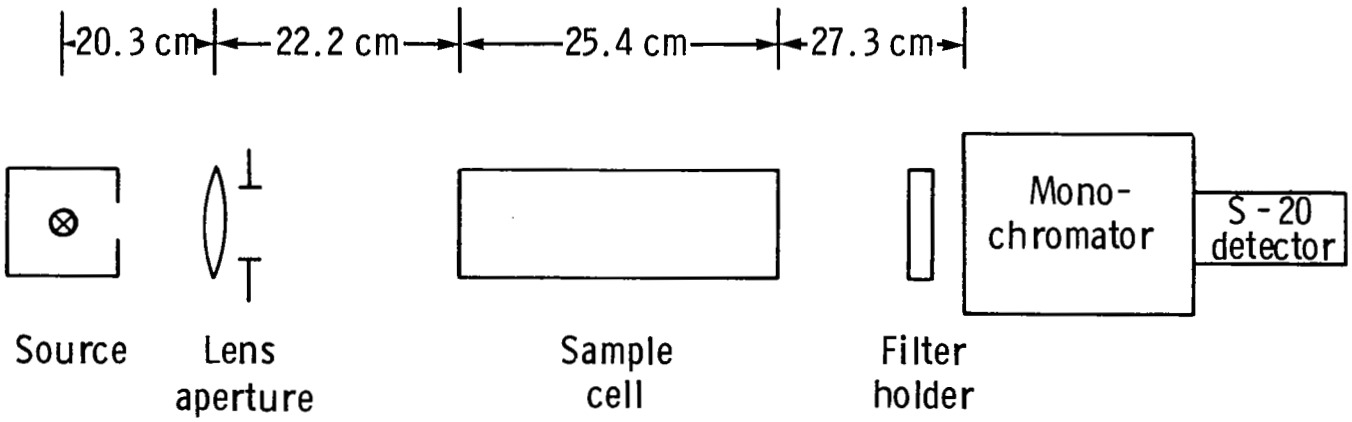

Figure 3.- Optical setup for this experiment.

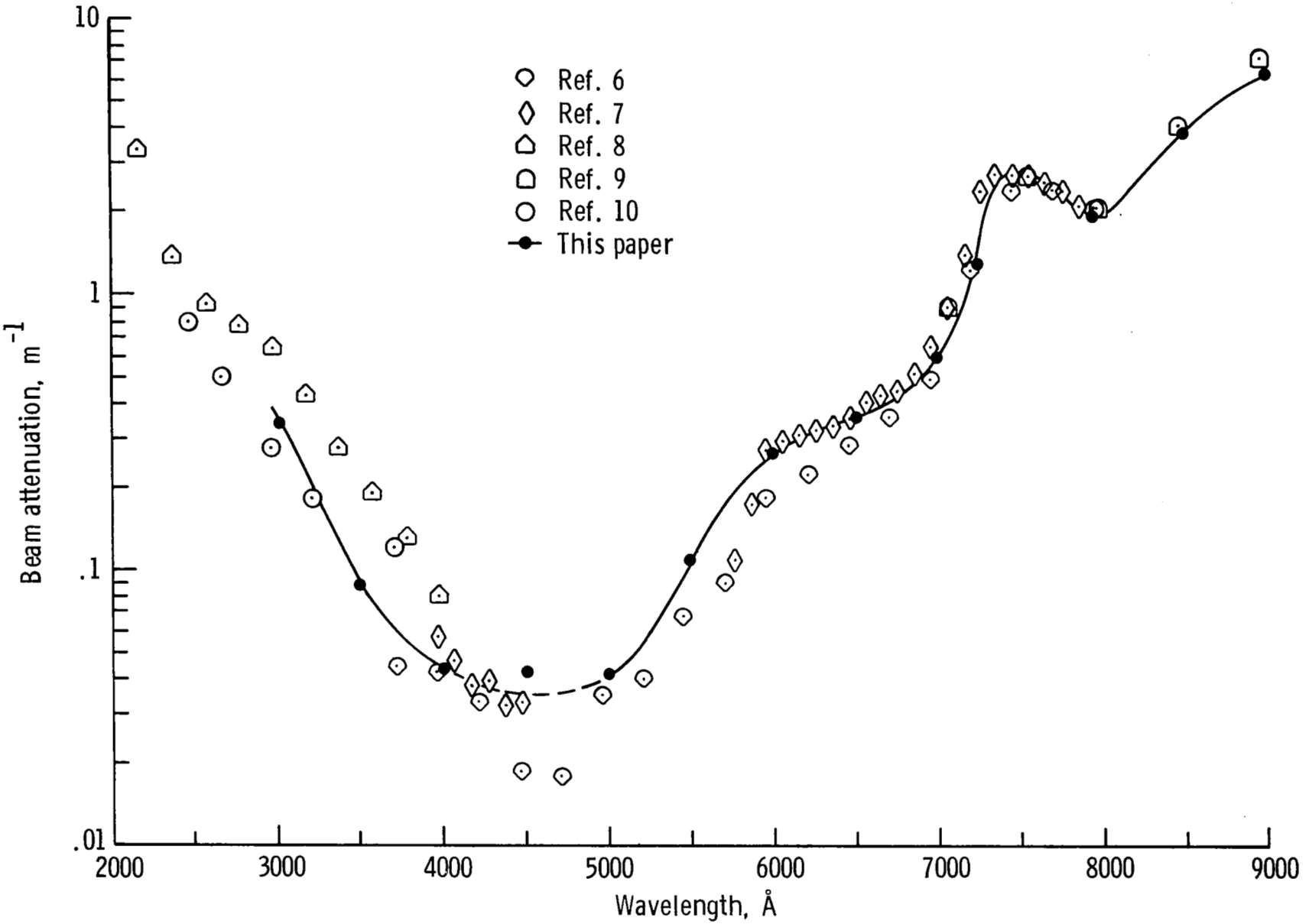

Figure 4.- Beam attenuation by pure water.

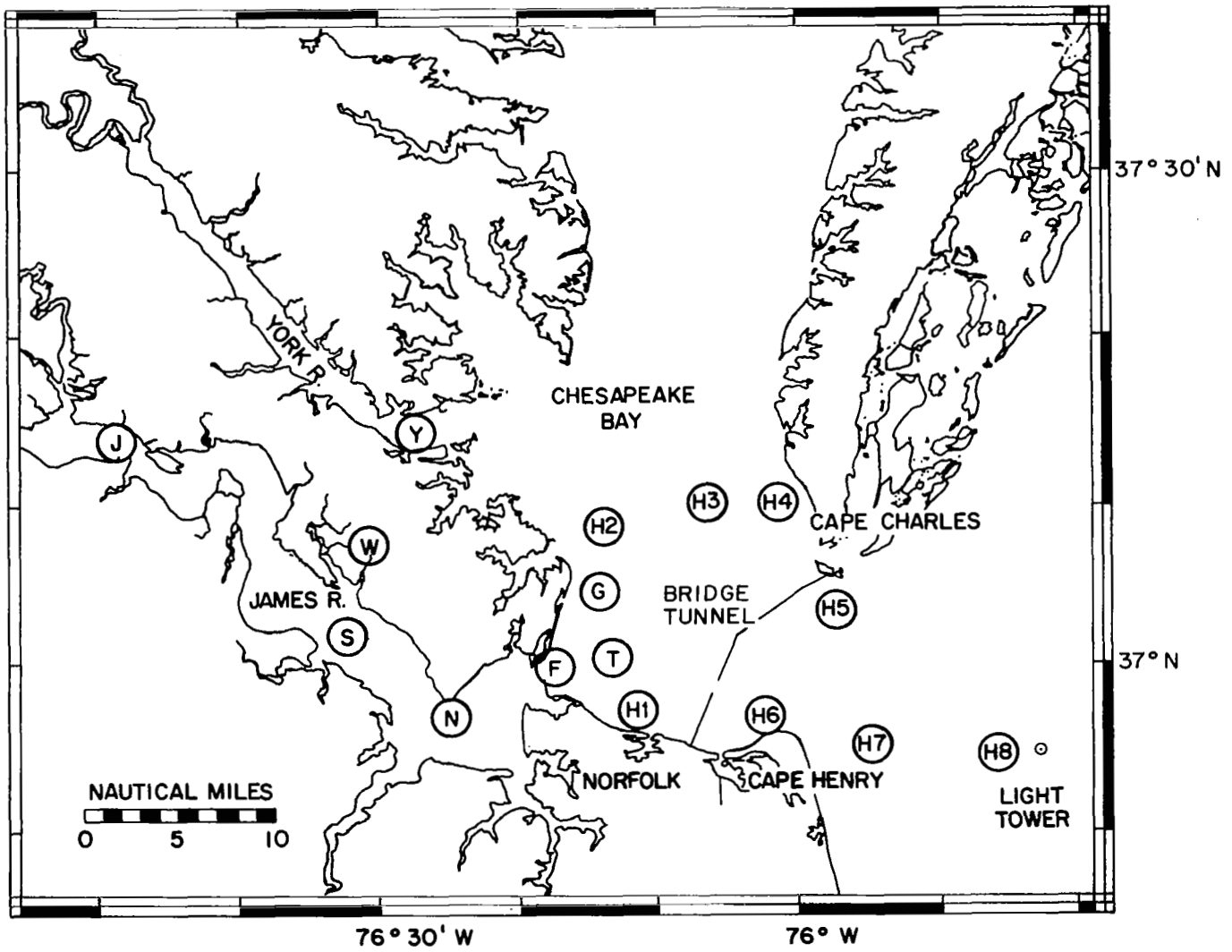

Figure 5.- Location of sample sites. See table II for pertinent data.

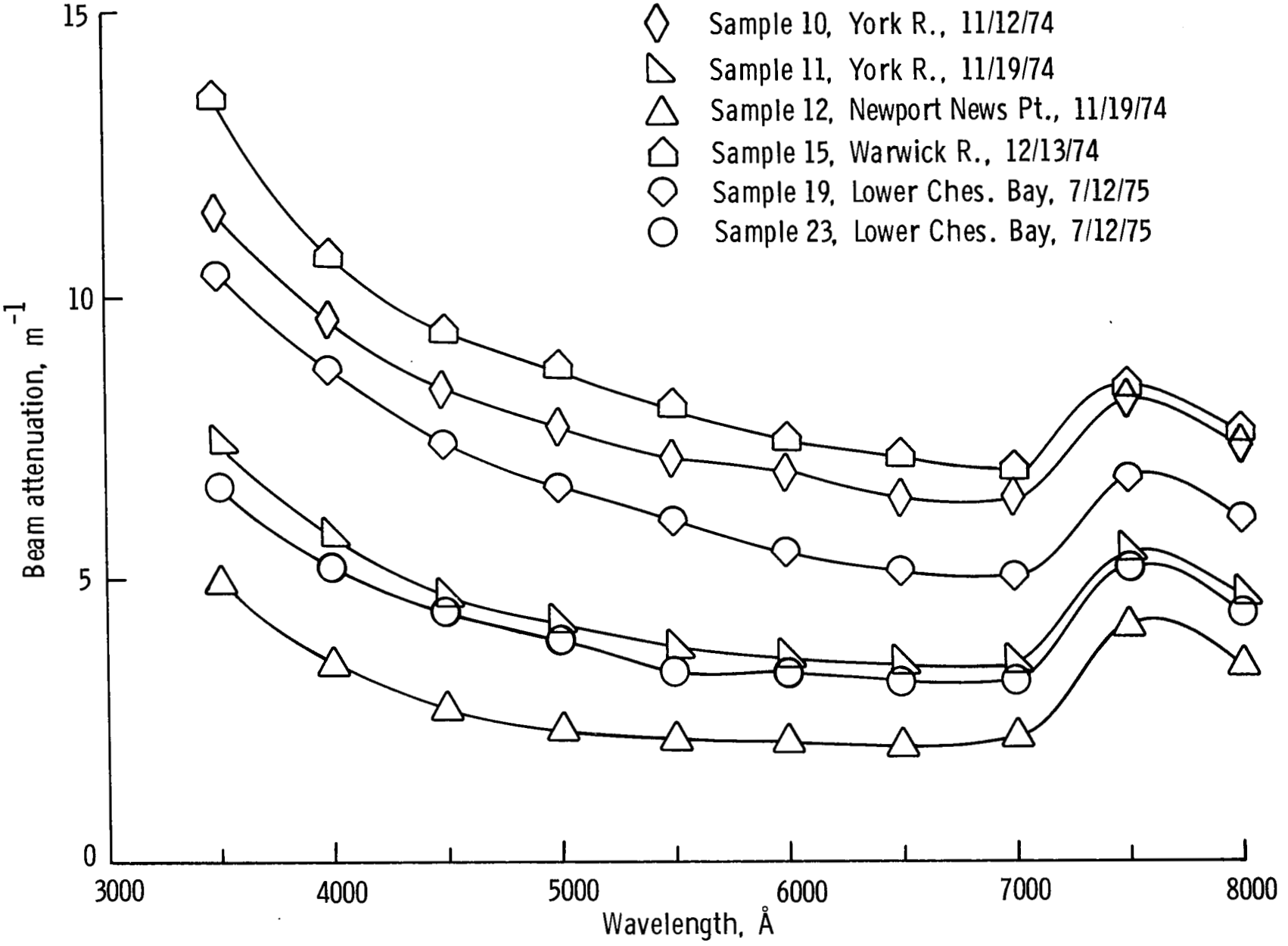

Figure 6.- Typical beam attenuation coefficients.

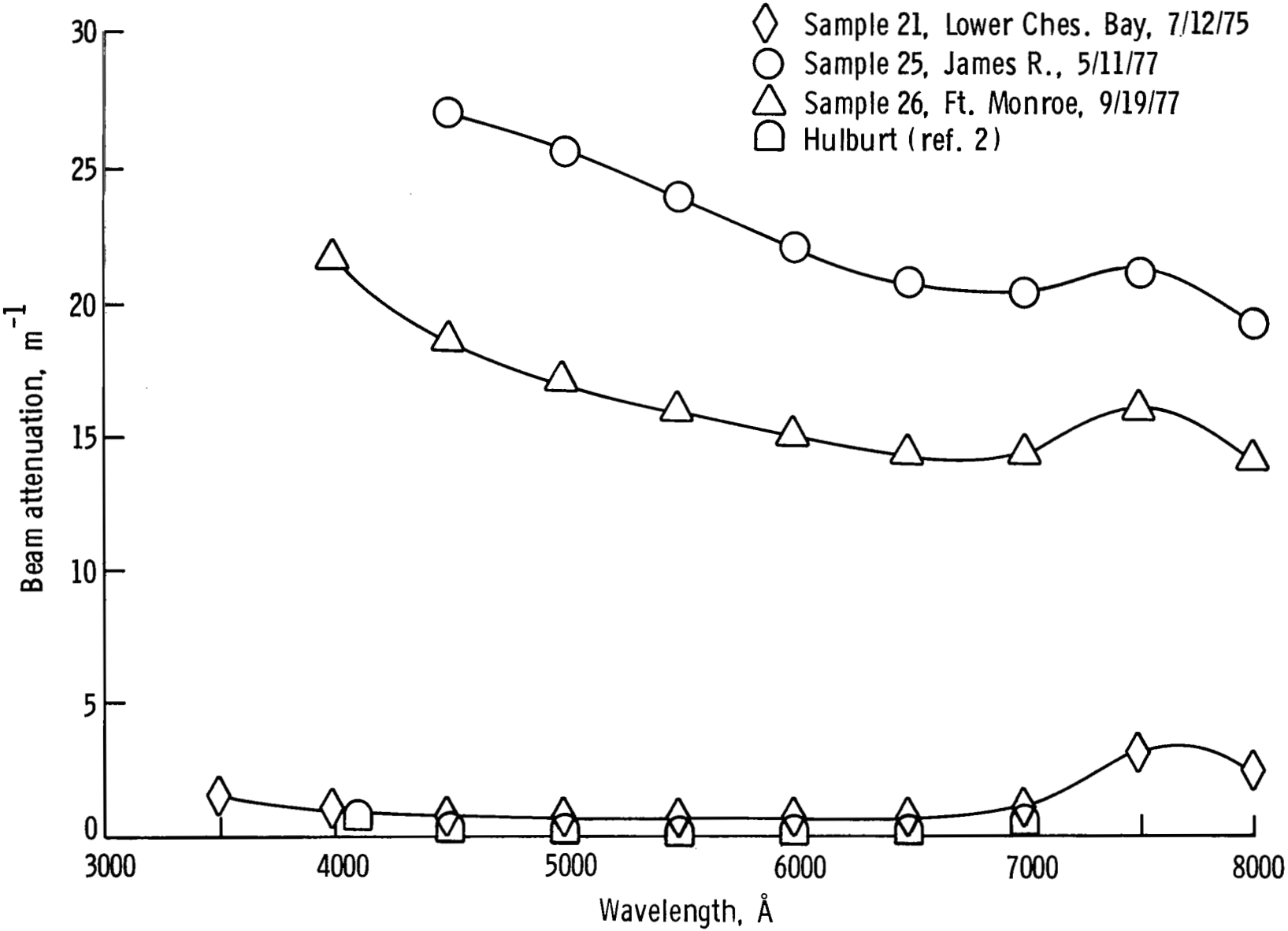

Figure 7.- Extreme beam attenuation coefficients.

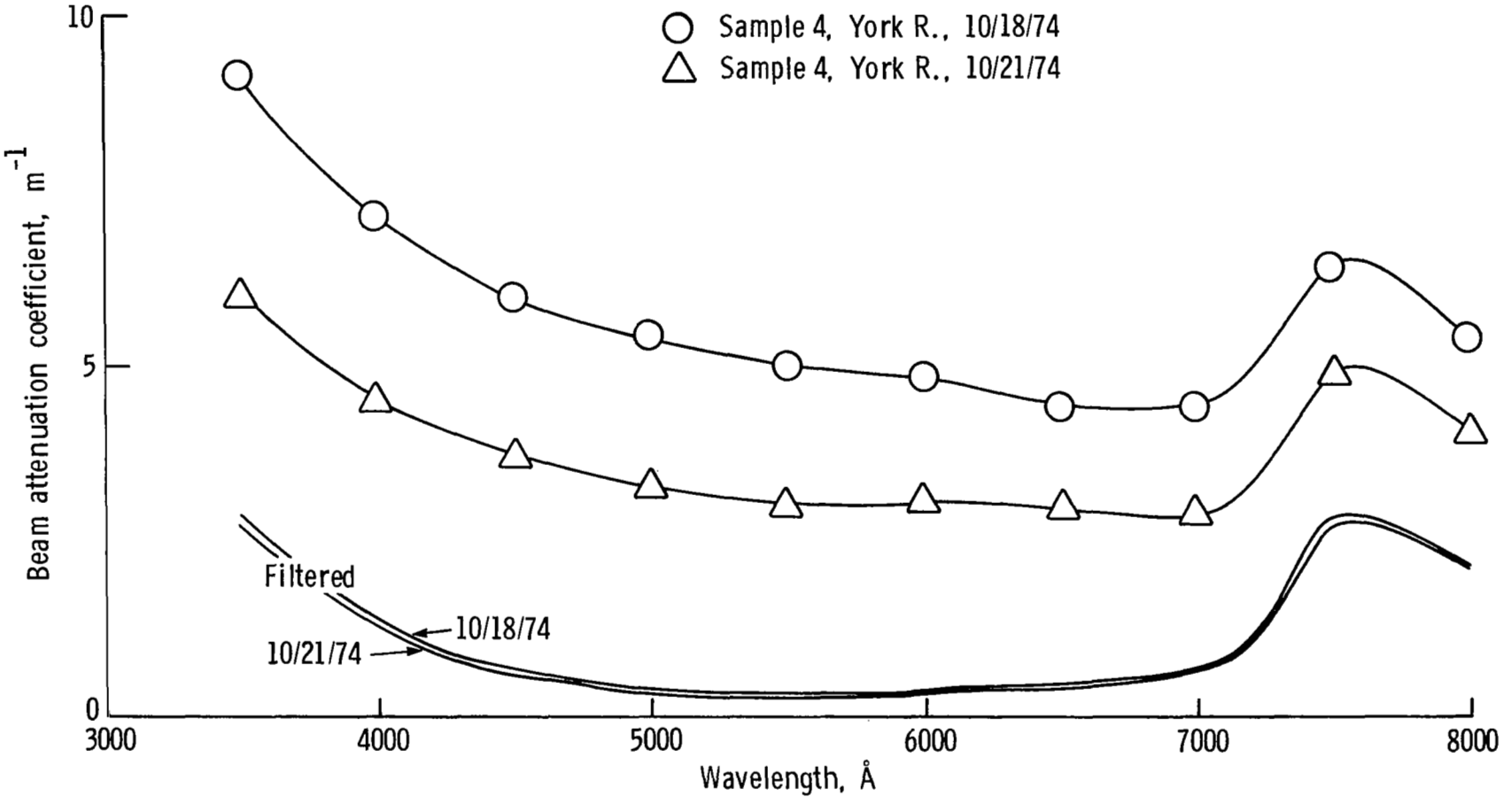

Figure 8.- Change in beam attenuation of sample 4 after 3 days.

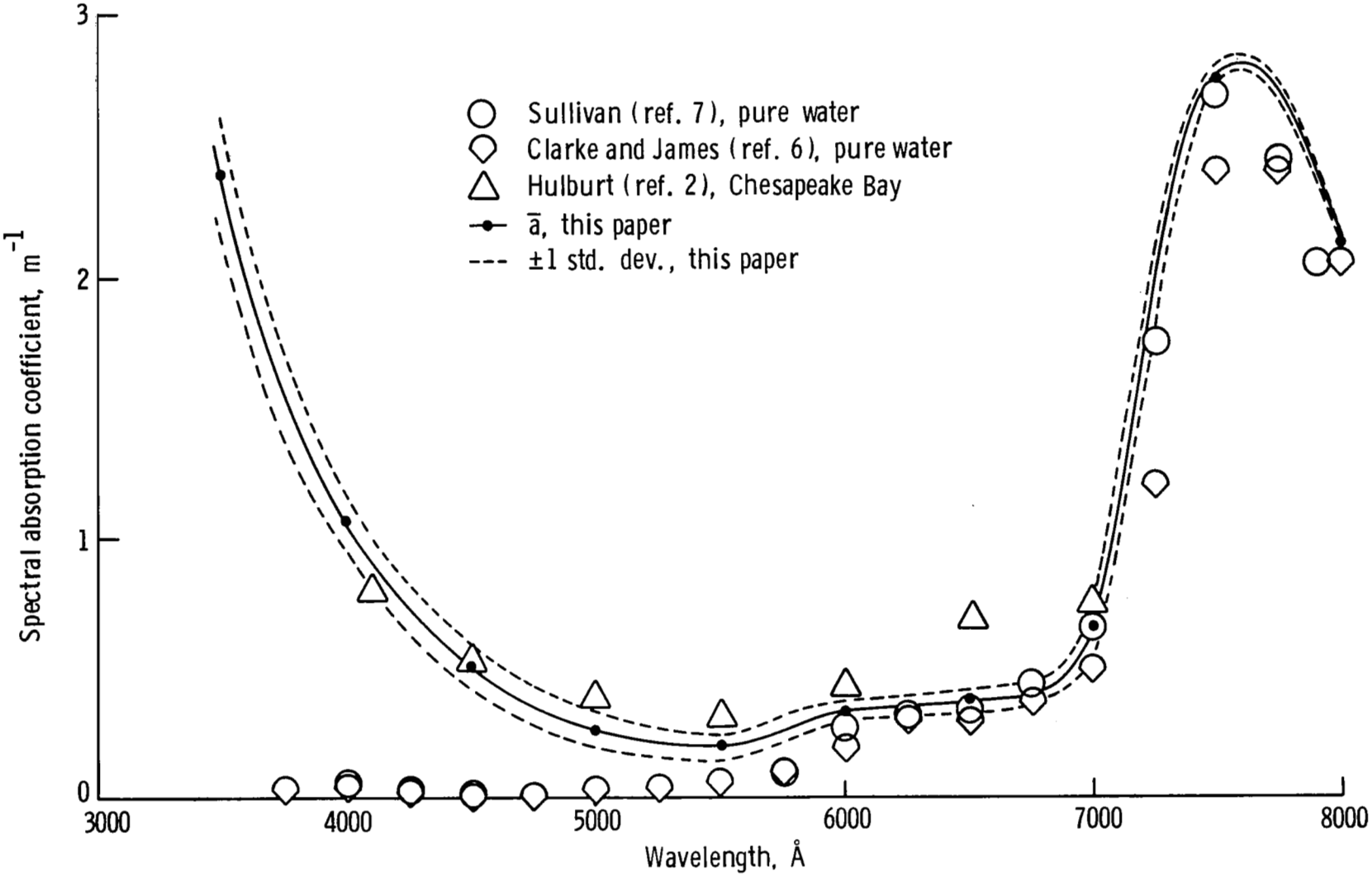

Figure 9.- Measured spectral absorption coefficients for filtered samples.

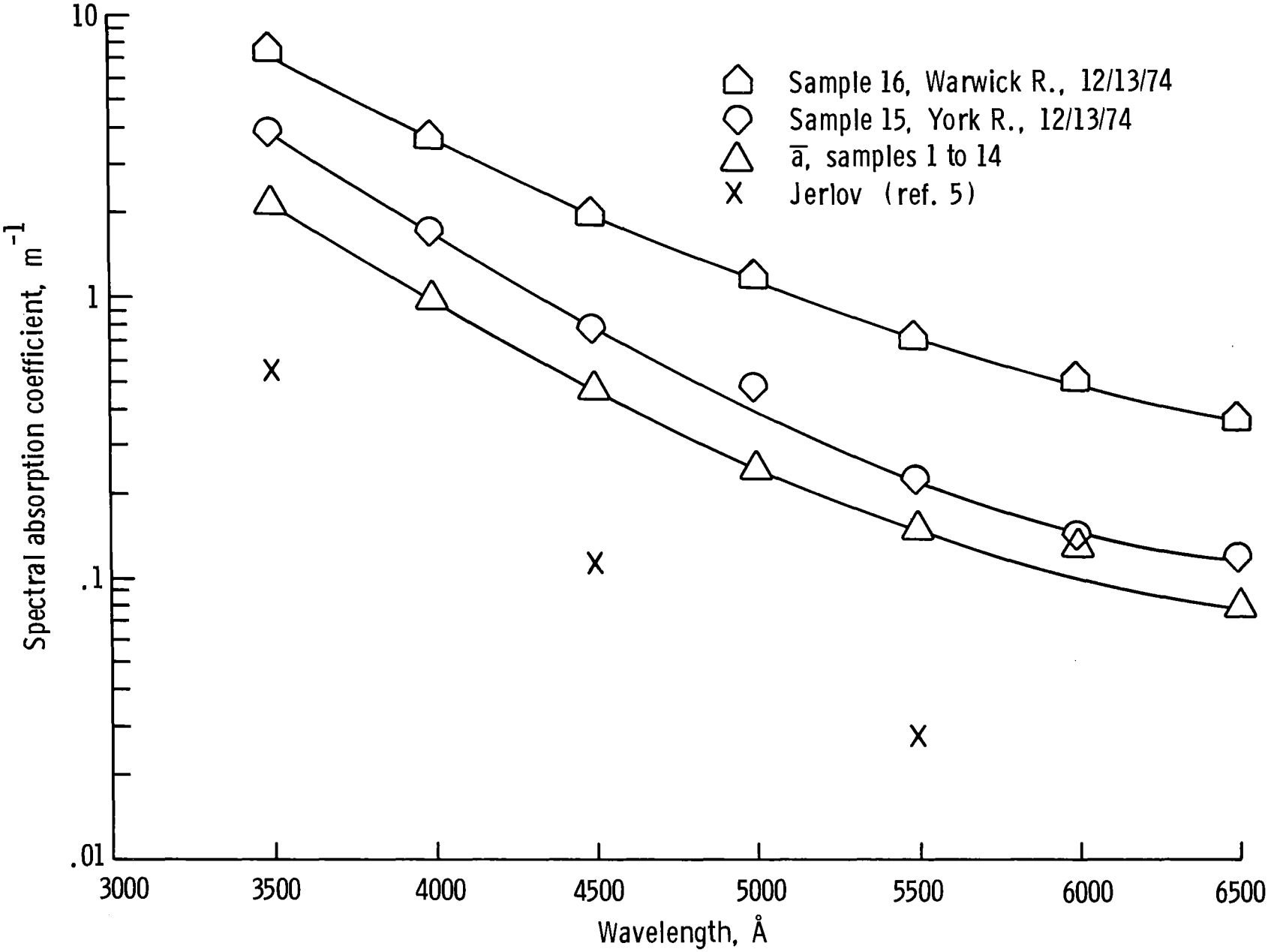

Figure 10.- Spectral absorption coefficients for DOM.

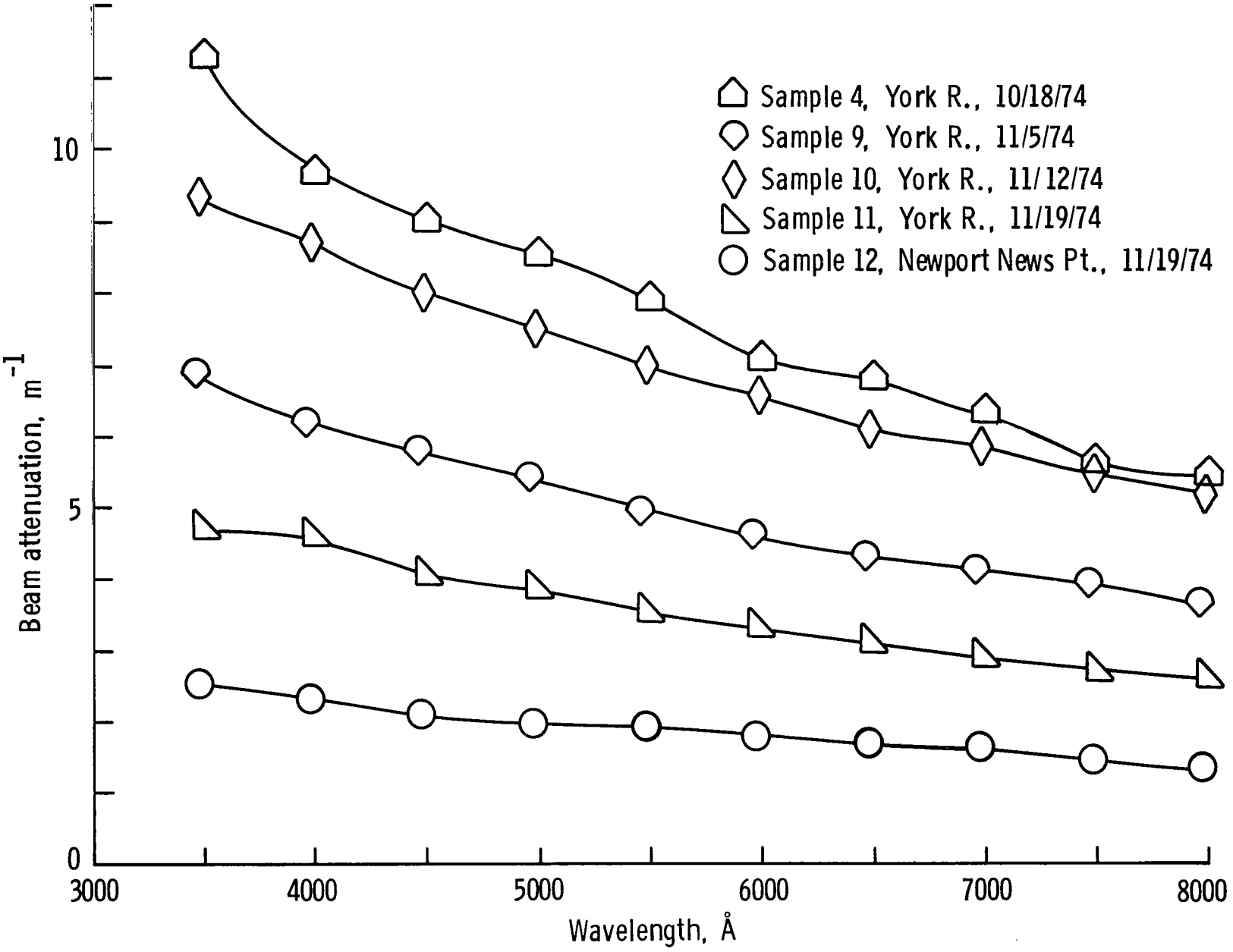

Figure 11.- Beam attenuation coefficients for particles.

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15. Supplementary Notes

16. Abstract

The spectral transmission was measured for water samples taken in the lower Chesapeake Bay to allow characterization of several optical properties. The coefficients of total attenuation, particle attenuation, and absorption by dissolved organic matter were determined over a wavelength range from 3500 Å to 8000 Å. The data were taken over a 3-year period and at a number of sites so that an indication of spatial and temporal variations could be obtained. The attenuations determined in this work are, on the average, 10 times greater than those obtained by Hulburt in 1944, which are commonly accepted in the literature for "Chesapeake Bay attenuation."

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