Long base line measurements of light transmission in clear water

Hugh Bradner and Grant Blackinton

Measurements have been made of the uncollimated (poor geometry) $1/e$ transmission distance of light in seawater at ~1200- and 780-m depths, 34 km west of Keahole Point, Hawaii. The measurements were made with 480-nm blue-green light through path lengths of 84.0 and 7.86 m. Transmission distance is determined to be 25.9 m ±1 m at 1.2-km depth and 24.4 m ±1 m at 780-m depth.

I. Introduction

The attenuation length of light in seawater usually is measured with a rigid instrument having a well-collimated light path ~1 m long. Both scattering and absorption reduce the light flux that reaches the detector. Such highly collimated measurements are important for establishing the fundamental optical properties of the seawater and for characterizing its image-forming characteristics. Experiments such as DUMAND (deep underwater muon and neutrino detection), however, are interested in photon collection rather than image formation. Furthermore, well-recognized difficulties exist in measuring the attenuation length with short light path instruments in very clear water. For example, the attenuation length of blue-green light in very clear seawater is of the order of 30 m producing an attenuation of $1 - \exp(-0.03)$ or 3% in a 1-m path length. Thus experiments must be done skillfully to yield accurate values of attenuation length. For this reason short light path measurements often are made with red light whose intensity is reduced by 20% or more in reaching the detector. The attenuation length for blue-green light is then calculated by using laboratory measurements of pure-water attenuation at different wavelengths. Unfortunately, the published ratios for red/blue-green attenuation coefficients differ by almost a factor of 2.[1]

For these reasons measurements were made near the DUMAND site west of Keahole Point, Hawaii by using an uncollimated instrument with a variable light path up to 84 m long. We use the term transmission distance β to avoid confusion between these uncollimated measurements and the more common collimated beam measurements. Optical oceanographers calculate attenuation coefficient α from collimated beam measurements. In very clear seawater β is nearly the reciprocal of α.

CTD and particulate concentrations in the DUMAND area have been reported by Zaneveld.[2] Salinity, oxygen, temperature, fluorescence, and pigment concentration have been measured in the same area by Lewitus.[3]

II. Instrument

The instrument is basically a wide-angle pulsed light source hung on a wire below a photodetector as shown schematically in Fig. 1. The output of the photodetector is integrated, digitized, and tone coded as shown in Fig. 2 and sent to shipboard for recording and monitoring. Observations are made at two or more source–detector distances to eliminate the need for absolute calibration of source and detector.

The source is a voltage-regulated commercial photostrobe (Sunpak 420) in a 13-cm diam cylindrical aluminum pressure case. An RC solid state timer triggers the flash every half minute. A 23-cm diam opal glass on the front of a commercial photoflood reflector produces the intensity distribution in water shown in Fig. 3 (curve labeled source).

The wire connecting source to detector is 3-mm (1/8-in.) diam clean stainless steel. The optical path length of a measurement is set by choice of preassembled connecting wire.

The detector is housed in a 20-cm diam cylindrical aluminum pressure case with a conical Lucite window. Light entering through the window passes through a 480-nm wavelength 10-nm bandwidth interference filter. It is detected by an EG&G model HUV 4000B

Hugh Bradner is with University of California, Scripps Institution of Geophysics, La Jolla, California 92093, and Grant Blackinton is with University of Hawaii, Hawaii Institute of Geophysics, Honolulu, Hawaii 96822.

Received 15 June 1983.
0003-6935/84/071009-04$02.00/0.

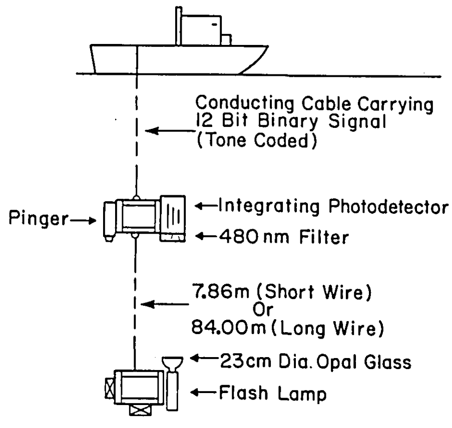

Fig. 1. System schematic.

silicon photodiode module that has an incorporated operational amplifier.

The HUV 4000B is hermetically sealed for stability of components including a 200-MΩ feedback resistor on the operational amplifier (op-amp). For measurements with the 84-m light path the HUV 4000B was used at full gain; for measurements with the 7.86-m light path an external 401 kΩ was connected in parallel with the 200-MΩ internal resistor. Calibration procedures for this change in sensitivity are described in Sec. V.

The output of the HUV 4000B is integrated by an OP-07 ultralow offset op-amp. The integrator output is reset to +4 V every 4 sec. The millisecond duration light pulse produces an abrupt negative step in the integrated voltage. The nonzero dark output of the HUV 4000B produces a slow drift in the integrated voltage, which is removed in calculating the pulse amplitude.

The integrated signal is digitized by a Burr Brown ADC 80, then put into 12-bit serial form, tone coded, and transmitted via (1/4 in.) hydrographic cable to shipboard.

On board ship the signal is split for monitoring on an oscilloscope, tone code digital recording on magnetic tape cassette, and analog recording on strip chart. The digital tape is later read by an onshore computer for accurate data analysis.

III. Data Analysis

Scattering of blue-green light in clear ocean water is sharply peaked forward and has a coefficient in good geometry experiments only ~10% as large as the absorption coefficient.[4] Therefore, attenuation of point-source monochromatic light can be considered exponential. The intensity from initial I_0 after traveling short path $S = 7.86$ m or long path $L = 84.00$ m can be written as

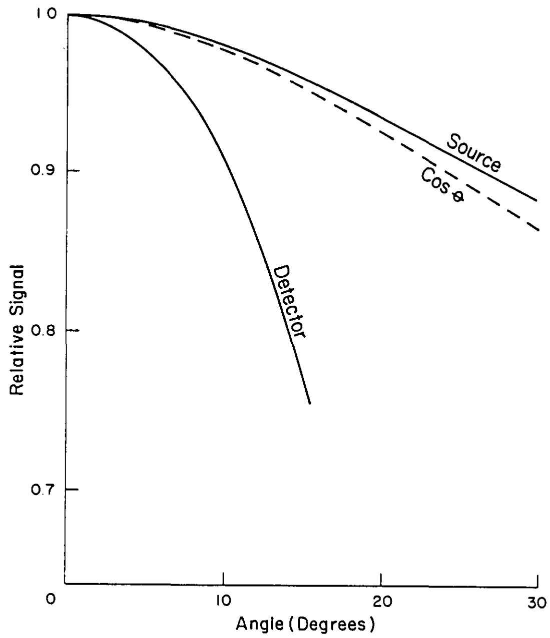

Fig. 3. Effect of misalignment on detected light intensity.

$$I_s = I_0 \exp(-S/\beta)/S^2 \qquad I_L = I_0 \exp(-L/\beta)/L^2. \tag{1}$$

Combining, we get the $1/e$ transmission distance

$$\beta = (L - S)/\ln(S^2 I_S/L^2 I_L) = 76.13/\ln(0.00878 I_S/I_L). \tag{2}$$

Note from Eq. (2) that the sensitivity of β to changes in I is

$$\delta\beta/\beta = \beta/(L - S)(\delta I_L/I_L) \tag{3}$$

and a similar expression, except for sign, for $\delta I_S/I_S$. In our experiments β is ~25 m, so

$$\begin{aligned}\delta\beta/\beta &\doteq 1/3(\delta I_L/I_L)\\ &\doteq -1/3(\delta I_S/I_S).\end{aligned} \tag{4}$$

IV. Observations and Results

Measurements were made at two depths near the east edge of the DUMAND Keahole site using source–detector separation distances of 7.86 and 84.0 m. Locations were 19°48′N; 156°24′W for the short wire and 19°50′N; 156°25′W for the long wire. Depths, determined by amount of cable payed out, were 1 and 1.5 km. (More accurate depths, determined by an acoustic pinger attached to the photodetector frame, are shown in Table III.)

As will be indicated in Sec. V, pulse-to-pulse variations can be attributed to relative motion of source and detector and always will result in reduced recorded intensity. For this reason the data are separated into

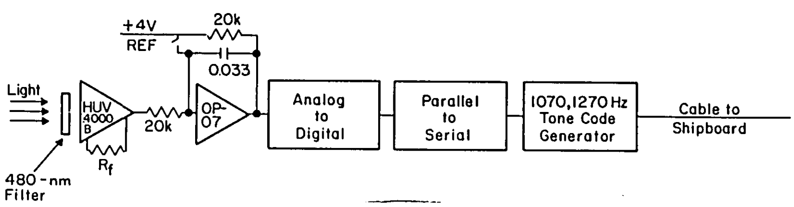

Fig. 2. Photodetector schematic.

Table I. Values of Recorded Signals I_S and I_L, Exponential Transmission Distance β, and Corresponding Statistical Uncertainties

Depth (m)	Samples	I_S[b]	σ (%)	I_L[b]	σ (%)	β (m)	σ (%)
780[a]	Highest 3	2061	—	343.7	—	24.4	—
	Upper half	2019	2.3	337	2	24.4	1
	All	1910	6.7	305.9	12	24.1	4.6
1200[a]	Highest 3	2032	—	402.7	—	25.9	—
	Upper half	1985	2.5	381.1	5	25.6	1.9
	All	1908	5.2	352.5	10	25.3	3.8
Combined	Highest 3	2065	—	402.7	—	25.7	—
	Upper half	2003	2.6	360.2	7	25.1	2.6
	All	1910	6.1	330.5	13	24.7	4.8
	Highest I_S vs all I_L	2065	—	330.5	13	24.1	—

[a] Nominal depths were 780 and 1200 m. See text for details.
[b] Arbitrary digital units.

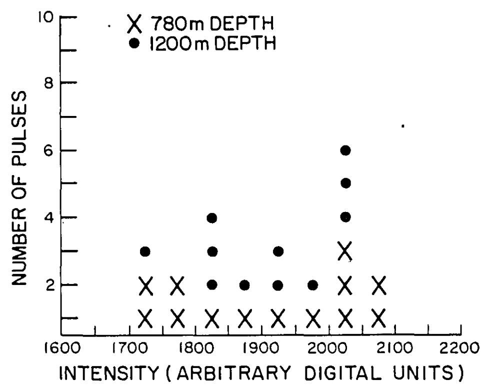

Fig. 4. Received intensity, short cable.

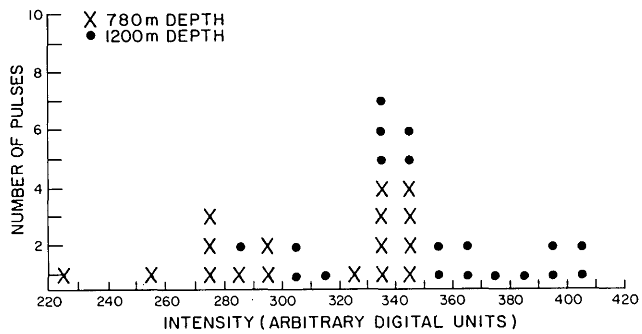

Fig. 5. Received intensity, long cable.

three groups: the average of the three highest received pulses; the average of the upper half of received pulses; and the average of all received pulses. Observed values of transmitted light are summarized in Table I. The two right-hand columns show the calculated values of β for various data groups and the percent uncertainty of β based only on the standard deviation of recorded intensities for all pulses in the group. The full distributions of received pulses are shown in Figs. 4 and 5. Note that the transmission distance differs by only ~5% at the two depths; therefore, Table I also shows our data with all our observed values at the two depths combined.

Table II. Effects of Major Uncertainties

	$\delta\beta/\beta$ (%)
Size of source (spreading is not $1/R^2$)	<+0.03
Cable length (±2 mm for S; ±1 cm for L)	<±0.02
Cable twist	−2, +2.2
Source and detector tilt	±1
Pulse-to-pulse source variation	±0.7
Detector gain calibration	±0.2
Worst case sum	−4, +4.2

V. Discussion

The most significant corrections and uncertainties to the calculated value of β are shown in Table II and are discussed below. $\delta\beta/\beta$ is the calculated 1σ value where applicable. A positive value of $\delta\beta/\beta$ indicates that the calculated value of β is greater than its true value.

A. Twist

Twist in the 3-mm diam wire connecting source to detector will move them out of optical alignment, thus reducing received light because of off-axis illumination and increased separation. The most severe effect is 5.5° misalignment for the 7.86-m wire when the source is twisted 180° away from the detector. Figure 3 shows that the apparent source level for this case is reduced by a factor of 0.995; the detector sensitivity is reduced by a factor of 0.975; and the correction for path length is 0.990, for a total intensity reduction factor of 0.960. The effects for the 84-m wire are negligibly small.

Additional effects near the 180° twist are the partial obscuring of the light beam by the 7.86-m wire and a further obscuring of the light beam by a 4.7-cm o.d. shackle in the 84-m wire. If all light striking the wire is lost from the detector, the intensity will be reduced by 3%. The shackle produces an additional 3% reduction. Combining all the above gives worst case intensity corrections of

$$\delta I_S/I_S = -6.5\%,\ \delta I_L/I_L = -6\%,\ \text{or}\ \delta\beta/\beta = -2, +2.2\%.$$

Table III. Cable Length vs Instrument Depth Determined by Acoustic Pinger

Date	Time	Wire length (m)	Length of cable payed out (m)	Instrument depth (m)
7/9/80	2020Z	7.87	1000	789
	2040			758
	2048		1500	1211
	2102			1116
7/10/80	1058Z	84	1000	870
	1106			872
	1113		1500	1339
	1125			1290

B. Source and Detector Tilt

The alignment was adjusted in calm seawater to better than 2°; this uncertainty in alignment can be seen from Fig. 2 to give uncertainty of <1/2% in intensity or <1/6% in $\delta\beta/\beta$.

Surface currents and winds at the Keahole site caused the ship to drift at ~1 kt, but the water at instrument depth moved much slower. Thus the instrument was dragged through the water at a quasi-steady speed of ~1 kt or 50 cm/sec. The effect of this current shear could be seen visually in the wire angle of the signal cable from the ship and on the acoustic depth record, which showed as much as a 20-m/min decrease in instrument depth for several minutes after the instrument was lowered to an intended cable length of 1 or 1.5 km. Recorded depths vs times are shown in Table III. The wire connecting detector to source hung in a path that was approximately parabolic, causing them to be optically misaligned. (The wire hangs more like a uniformly loaded suspension bridge than a free-hanging catenary cable.) As shown in Fig. 2, detector alignment is more critical than source alignment. In a 1-kt current the equilibrium source misalignment was calculated to be ~1° due to water drag; oscillations of five times this amplitude due to flowing water would lead to <2% reduction in signal or $\delta\beta/\beta < 2/3\%$. An upper limit of combined tilt effects is taken to be 1%.

All these rotations and misalignments would result in weaker received intensities. As either the short or the long cable signal could suffer reduction, however, the effect could cause either an increase or a decrease in β.

C. Pulse-to-Pulse Variation of Strobe Source

The charging time between flashes is <10 sec, and the flash rate is 2/min. At this repetition rate, integrated light output measured in the laboratory is independent of supply voltage between at least 4.5 and 6.5 V and is constant from pulse to pulse with standard deviation of 0.67%. In a test run of 33 flashes the maximum integrated output exceeded the average by <1.5%, so the uncertainty was taken to be 2%, giving $\delta\beta/\beta = 0.7\%$. Capacitance of the energy-storage capacitors decreases 4% when cooled from 24 to 0°C, but this decrease is unimporant because the aluminum capacitor case is held tightly against the aluminum pressure case, thus bringing its temperature essentially to that of surrounding seawater before light transmission measurements are made for either path length.

D. Detector Gain Calibration

The ratio of detector gains used with the two wire lengths was determined in the laboratory. A two-step process with a stabilized dc incandescent lamp was employed for maximum accuracy in determining the large gain ratio (428.0). The output of the HUV 4000B at one light intensity was measured with a digital voltmeter for a reference 9.00 MΩ vs the 401-kΩ resistor used in the sea measurements; and the output at another light intensity was measured for the 9.00 MΩ vs the unshunted (namely, 200-MΩ) condition. The standard deviation of repeated measurements was 0.05% for 9.00 MΩ vs 401 kΩ and 0.2% for 9.00 MΩ vs 200 MΩ. The reduced accuracy in the latter case was caused by the increased amplifier drift at 200 MΩ. The temperature coefficient for the HUV 4000B with its 200-MΩ internal resistor is claimed to be ~0.01%/°C.

E. Total Errors

These uncertainties cannot be combined statistically in a straightforward way, so a rounded arithmetic sum was used as the worst case sum of errors of −4% +4.2%.

An alternative approach to error analysis is to consider the pulse-to-pulse variation in light recorded during the observations at sea. The data presented in Table I show standard deviations in good agreement with the preceding error analysis if $\delta\beta/\beta \doteq \sigma/3$.

As an indicator of reliability we have also calculated β by using the highest values for I_S and all the values for I_L. The resulting β is 24.12 m.

VI. Conclusion

The $1/e$ transmission distance of light in seawater at ~1200-m depth 34 km west of Keahole Point, Haw. calculated from the three highest pulses is $\beta = 25.9$ m. The value calculated from all data at this depth is 25.3 m. Corresponding values at ~780-m depth are $\beta = 24.4$ m and $\beta = 24.1$ m. Probable errors cannot be fully described statistically, but the error analyses made by three different methods lead to estimates for $\delta\beta$ of ±1 m.

This work was supported by the Office of Naval Research and the Hawaii Institute of Geophysics. Publication was supported by a grant from the Foundation for Ocean Research, La Jolla, Calif. This is HIG contribution 1444.

References

1. See, for example, R. C. Smith and K. S. Baker, Appl. Opt. **20,** 177 (1981).
2. J. Ronald V. Zaneveld, "Optical Properties of the Keahole DUMAND Site," in *Proceedings 1980 DUMAND Symposium, Vol. 1*, V. J. Stenger, Ed. (Hawaii DUMAND Center, Honolulu, 1981), p. 1–8.
3. A. Lewitus, Vertex 4 Cruise Technical Report, Moss Landing Marine Laboratories (1984), in preparation.
4. See, for example, A. Morel, "Optical Properties of Pure Water and Pure Sea Water," in *Optical Aspects of Oceanography*, N. Jerlov and E. S. Nielsen, Eds. (Academic, New York, 1974).