NRL Report 5941

Transmission of Ruby Laser Light Through Water

J. A. Curcio and G. L. Knestrick

Radiometry Branch
Optics Division

APPROVED FOR PUBLIC
RELEASE - DISTRIBUTION
UNLIMITED

June 18, 1963

U.S. NAVAL RESEARCH LABORATORY
Washington, D.C.

Transmission of Ruby Laser Light Through Water

J. A. CURCIO AND G. L. KNESTRICK

Radiometry Branch
Optics Division

The attenuation coefficients of filtered Potomac River water were measured at the ruby laser wavelength, 6943A, and at three wavelengths in the green region of the spectrum where the attenuation is near the minimum. The tests were conducted *in situ* at the David Taylor Model Basin. The path of the light beam, which was at a depth of 2.2 m, was varied from 6 to 36 m in the laser light observations and from 15 to 73 m for the green light observations. Narrow-band filters were used to restrict the passband of the system, and the field of view of the receiver was limited to 1.2 degrees. The attenuation coefficient obtained at 6943A was 5.45×10^{-3} cm^{-1}, and the value obtained at 4900A was 8.6×10^{-4} cm^{-1}. Evidence was found for some small particle scattering. As an underwater light source, the ruby laser is severely handicapped by the fact that its emission occurs at a wavelength which is highly attenuated by water.

INTRODUCTION

The transmission of light signals through water is a long and historic problem which has received considerable attention at NRL. The researches of Hulburt (1) on the attenuation coefficients of distilled water are the standard and basic work in this field. The introduction of the new laser light sources in the last several years has brought about renewed interest in the problem of light transmission through water. Some of this interest has been directed toward a search for so-called narrow transmission windows in the water absorption structure. The present work is concerned with the measurement of the attenuation of a specific type of laser light. The enthusiasm which has been generated by the laser as a possible source for underwater communication has been a stimulus for this work. Previous work in the laboratory and in the field has indicated that attenuation at the ruby laser emission is too severe for practical application. The present work was undertaken as a check on previous data and also to provide definite data for ruby laser light.

TRANSMISSION OF LIGHT THROUGH DISTILLED AND NATURAL WATER

The transmission of light through distilled water has been extensively studied by many workers. We note for example the work of Hulburt (1), Curcio and Petty (2), and more recently a high-resolution study in the visible region by Drummeter and Knestrick (3). Figure 1, taken from the work of Curcio and Petty, shows spectral attenuation coefficients for distilled water at 20°C in the wavelength interval from 0.70μ to 2.5μ. The regions of maximum absorption in this spectral interval occur at 0.76, 0.97, 1.19, 1.45, and 1.94μ. Transmission peaks occur at 0.80, 1.06, 1.25, 1.66, and 2.2μ. However, even at these transmission peaks the attenuation is very severe. For example, at 0.80μ where the attenuation coefficient* is 2×10^{-2} cm^{-1}, the transmission of 100 feet of distilled water is 8×10^{-27}. At 1.06μ, which is in the region of the neodymium glass laser emission, the attenuation coefficient is 1.2×10^{-1}, which corresponds to a transmission of 10^{-19} for only 10 feet of distilled water.

The spectral region where distilled water has maximum transmission is in the blue-green region from 4500 to 5500A. This is shown by Hulburt's curve in Fig. 2, which is taken from Ref. 1. These data show the minimum attenuation coefficient to be about 4×10^{-4} cm^{-1}, which corresponds to a transmission factor of 3×10^{-1} for 100 feet of distilled water. The attenuation coefficient for distilled water at the ruby laser wavelength of

NRL Problem A02-17, Project RR 004-02-42-5152. This is an interim report on one phase of the problem; work on this and other phases is continuing.

Manuscript submitted March 5, 1963.

*The attenuation coefficient σ can be defined as the sum of three terms: σ_m is the molecular scattering coefficient, σ_p is the particle scattering coefficient, and σ_a is the absorption coefficient. So, $\sigma = \sigma_m + \sigma_p + \sigma_a$.

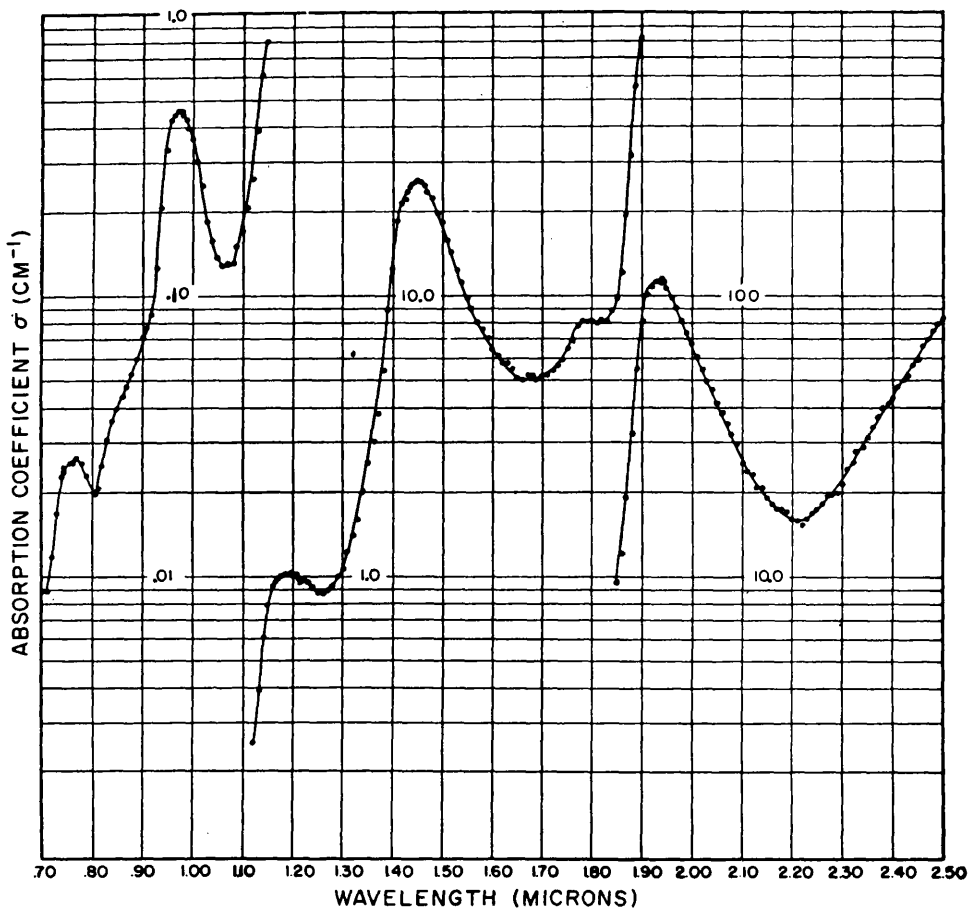

Fig. 1 - Near-infrared spectral absorption coefficients for distilled water at 20°C (from Ref. 2)

6940A is about 5×10^{-3} cm^{-1}, and this corresponds to a transmission of 1.1×10^{-7} for 100 feet of distilled water.

The transmission of light through natural waters has also been investigated by many workers (4-7). A recent report (8) from the U.S. Naval Ordnance Test Station has a convenient summary of the results of previous workers, including the results of Clarke and James at Vineyard Sound and of Hulburt on Chesapeake Bay water (Fig. 2).

The transmission of light through water is inversely proportional to the amount of light absorbed and scattered by the water. In addition to the molecular absorption in pure water (Fig. 1), there may be selective absorption by dissolved material in some natural waters. Molecular scattering arises from particles which are small compared with the wavelength of light (Rayleigh scattering) and varies as λ^{-4}, where λ is the wavelength of light. Generally, there is also additional scattering from material particles suspended in the water. When the particle radius is of the same magnitude as the wavelength of visible light, the particle scattering coefficient is a complex function of the wavelength and depends on the particle's size and composition. If the particles are many times larger than the wavelength of light, the attenuation coefficient is relatively nonselective with wavelength.

Techniques similar to those used in atmospheric optics have been applied by Burt (9) to the measurement of particle scattering in Chesapeake Bay water. The particle-size distribution was found to be of the form

$$V = be^{-c(\log r)^2} , \qquad (1)$$

where V is the volume of material of radius r, and b and c are constants which determine the mean radius and dispersion about the mean,

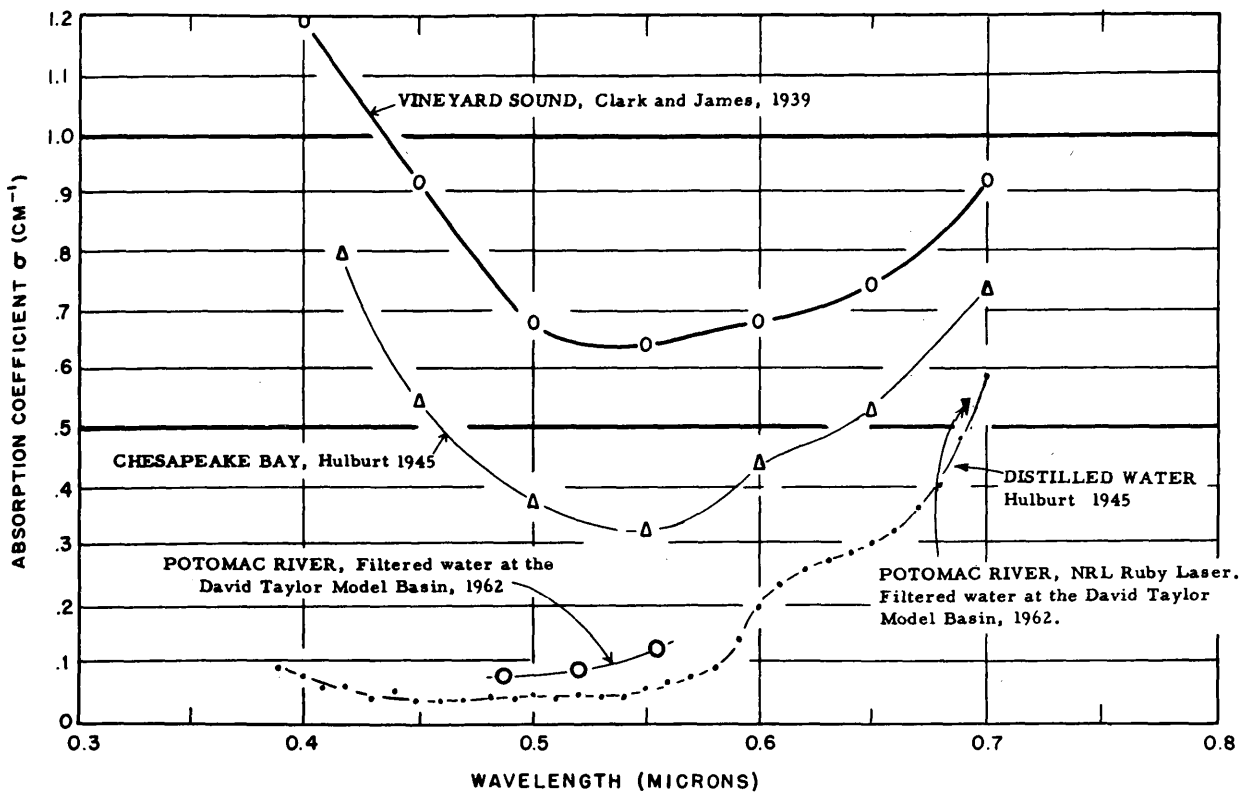

Fig. 2 - Spectral attenuation coefficients for water from various geographical locations (from Refs. 1 and 8)

respectively, for any distribution. The dispersion is the ratio of the 95th percentile of cumulative volume to that of the mass median (50th percentile). The average Chesapeake Bay water was found to have a log-normal particle-size distribution with a mass mean radius of 0.3μ and a dispersion factor of four. When the water was abnormally clear, the particles were better represented by a size distribution having a mass mean radius of 0.1μ and a dispersion factor of four.

MEASUREMENTS WITH RUBY LASER LIGHT

Equipment

In the present work two series of measurements were made of the attenuation coefficient of a particular water sample for the ruby laser wavelength of 6943A. The attenuation of green light was also determined through a series of measurements at three green wavelengths. The measurements were made *in situ* at the David Taylor Model Basin (DTMB), Carderock, Md., in one of the model testing basins. The basin was 25 ft wide and filled to a depth of approximately 10 ft with continuously filtered Potomac River water.

Light entered and emerged from the water through specially constructed 5-in.-diam. periscopes. The laser periscope was mounted on an electrically driven carriage which is used for towing models and which runs on precision guides. The receiver periscope was stationary at one end of the basin.

The optical system used for the first set of measurements is shown schematically in Fig. 3. The laser periscope unit consisted of a commercial laser head, a monitoring detector, a beam splitter, the periscope itself, and a sighting telescope. All windows were 1/4-in. plate glass, and the mirrors were front-surface-aluminized plate glass. The laser unit employed a 1/4-in.-diam. ruby rod 2-1/2 inches long and was operated at approximately 600 joules input. (The radiant energy of the laser was approximately 0.07 joule.) At this power level the laser beam had a 3/4-degree divergence. The beam splitter was a piece of glass 1/16 inch thick which reflected a small percentage of the

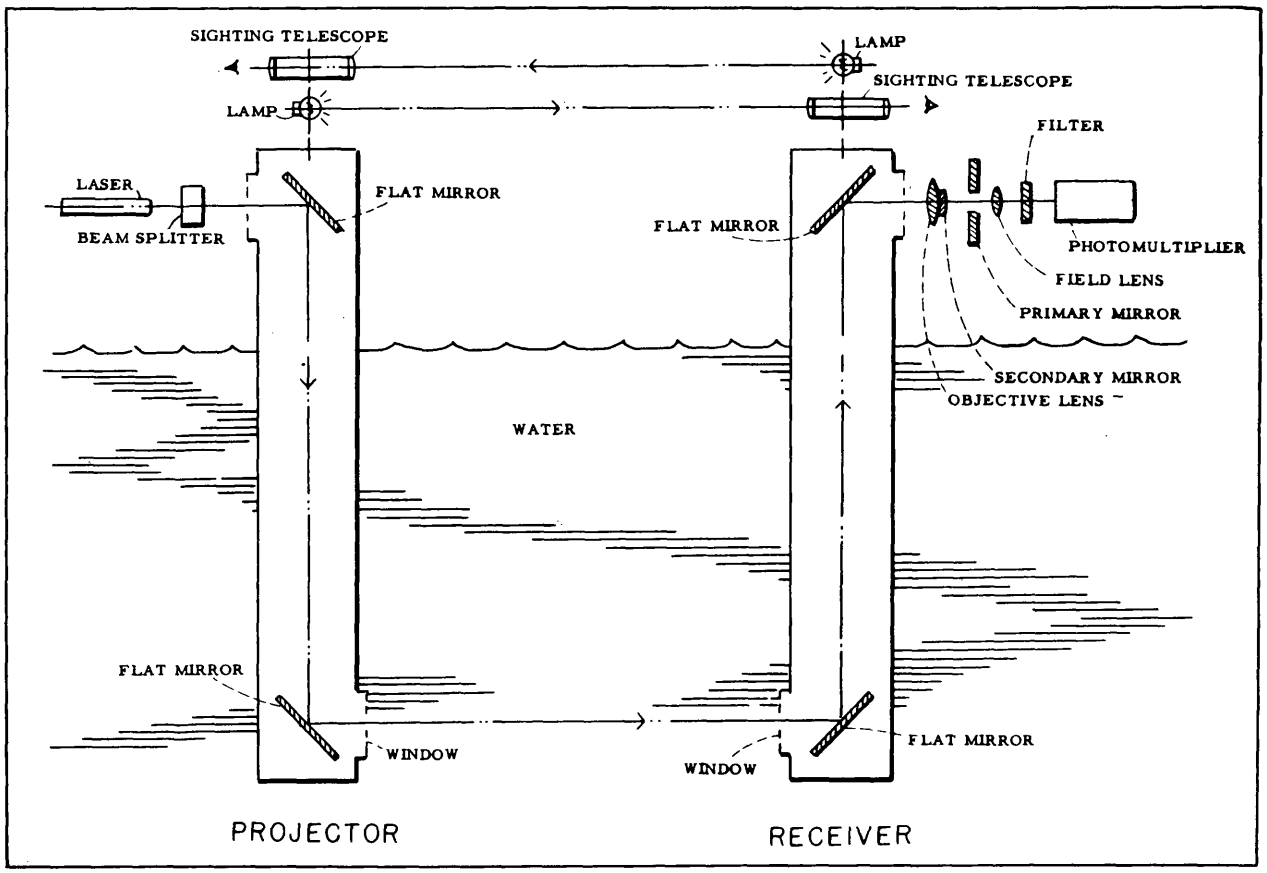

Fig. 3 - Schematic diagram of initial optical system

laser light to the monitor, a type 6911 photomultiplier tube which has an infrared sensitive photocathode. A 1/4-in. circular aperture and a Corning sharp-cut red filter were placed in front of the monitor to reject pump light which leaked out of the laser head. To prevent saturation of the monitor, the laser light was attenuated by a factor of 10^7 with gelatin filters.

The receiver periscope unit (Fig. 3) consisted of the periscope, an optical collector system, the photoelectric detector, and a sighting telescope. The collector system consisted of a 5-in. *f*/4 lens and mirror system with a field lens at its focus. A narrow-band interference filter with peak transmittance at 6943A was inserted behind the field lens. The bandwidth at half-peak transmittance was 8.5A for collimated light. It is estimated that in the *f*/4 divergent beam the half bandwidth was about 10A. The rejection ratio outside the passband was measured to be of the order of 10^6:1, with blocking extending to the infrared cutoff of the photomultiplier tube. The latter was a type 7265, 14-stage multiplier with S-20 response.

Before the periscope units were installed in the basin they were optically aligned and the sighting telescopes were boresighted. Figure 4 shows the laser periscope assembly installed in the DTMB carriage, and Fig. 5 shows the receiver periscope and associated electronics. The bottom windows of both periscopes are at a depth of 2.2 m. The periscopes were set approximately the same distance from one side of the basin and were plumbed. Small target lights were used with the sighting telescopes for pointing the periscopes at each measured distance (Fig. 3).

Measurements

The amount of transmitted light was measured at 9-m projector-to-receiver intervals from 9 m to 36 m and also at 41 m. Signals were read directly from the oscilloscope and corrected both

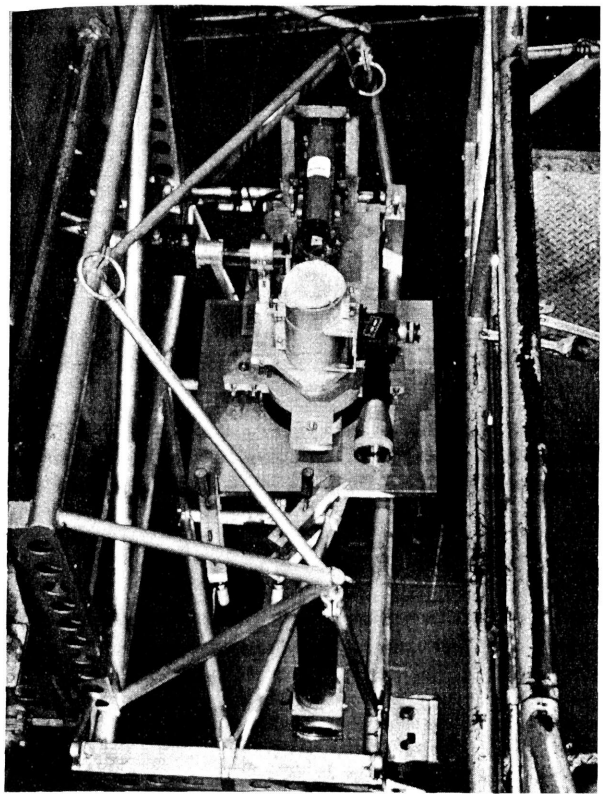

Fig. 4 - Laser periscope installed in carriage at DTMB

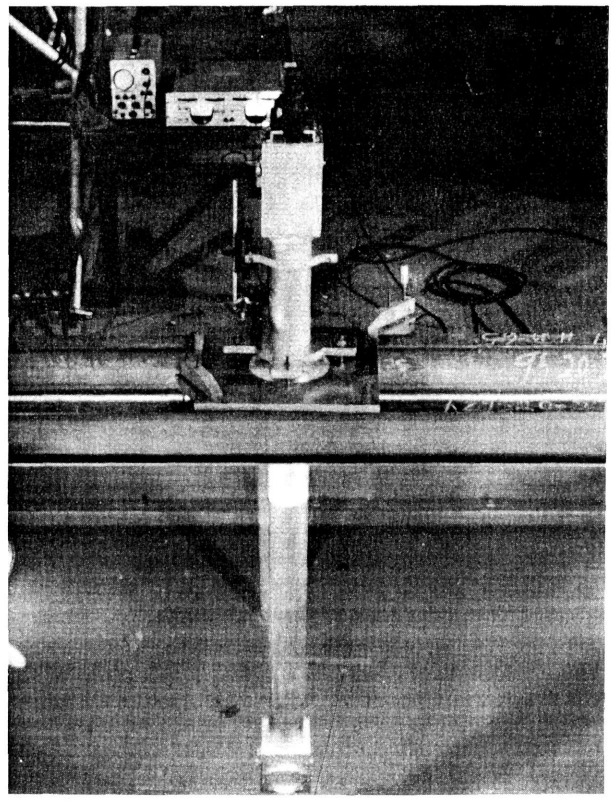

Fig. 5 - Receiver periscope installed in basin

for inverse square law and for multiplier tube gain changes and laser output variation as indicated by the monitor. The logarithms of the corrected signals were plotted as a function of the distance through water (Fig. 6). Using this curve, one can compute the attenuation coefficient since the expression for the curve is

$$I = I_o\, e^{-\sigma x},$$

or

$$ln\, I = ln\, I_o - \sigma x,$$

which may be differentiated to obtain the slope

$$m = \frac{d\, ln\, I}{dx} = -\sigma.$$

Since the signal $S = k\, I$, one obtains the relation

$$\frac{d\, ln\, S}{dx} = -\sigma.$$

Therefore, the attenuation coefficient is the slope of the straight line through the measured points.

The value of the slope in this case is $-0.53\ m^{-1}$. Therefore, the attenuation coefficient for filtered Potomac River water at 6943A was found to be $5.3 \times 10^{-3}\ cm^{-1}$. This value lies very close to the value for distilled water, $5.0 \times 10^{-3}\ cm^{-1}$, obtained from Hulburt's data (1) and is much lower than the coefficient quoted in Ref. (8) for sea water at this wavelength. Filtered river water could reasonably be expected to have less attenuation than sea water, but there was a question as to whether the values should approach those of distilled water.

On close examination of the technique used in the experiment, two possible sources of error appeared. The more likely of these was considered to be an uncertainty in the pointing of the periscopes, which was related to the boresighting of the sighting telescopes. The fixed focus of these items created a parallax problem at the relatively short distances used here. There was also a high probability that the boresighting could have been disturbed during the process of installing the periscopes in the basin.

The second possible source of error was associated with scattered light. This problem arose

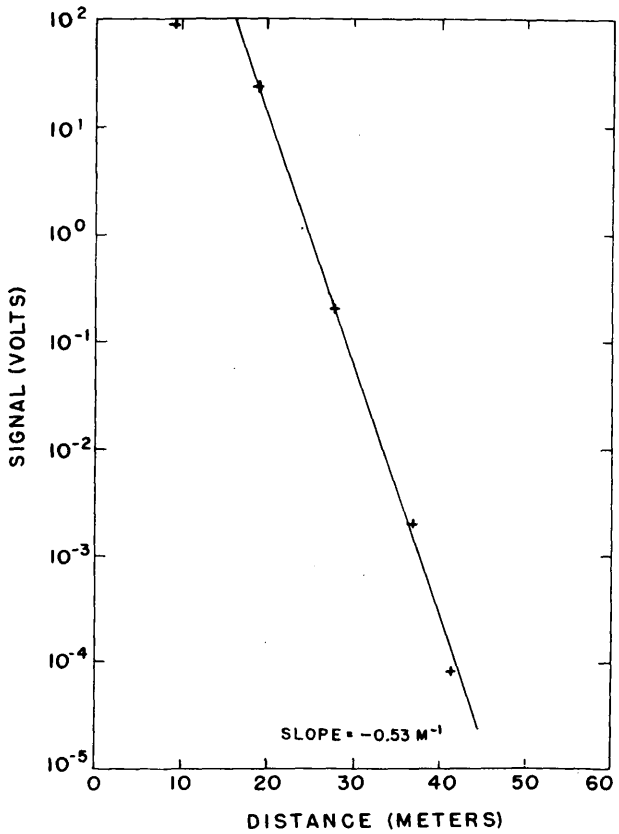

Fig. 6 - Relative transmissivity of Potomac River water at 6943A as obtained with the initial equipment

from a combination of circumstances, one being the issuance of pump light through joints in the laser head cover, around the end of the ruby rod, and even through the rod itself. Another circumstance contributing to the problem was the proportional increase in intensity of this pump light as compared to the laser light at the greater distances. (The stimulated emission is more rapidly attenuated with distance.) The actual transmission ratio of green to red light is about 10^7 for a 30-m path, which could possibly render a filter rejection factor of 10^6 inadequate.

Modifications

The laser beam was collimated by adding a 10-ft focal length *f*/80 lens at the exit window of the periscope, as shown in Fig. 7, the main reason being to eliminate any question as to what part of the beam was being observed. Scattered pump light was eliminated by enclosing the laser head in a black felt cover and by sealing off the area between the end of the ruby rod and the end plate of the laser housing. In order to reduce the pump light which was scattered out of the ruby itself, an iris diaphragm was added to the periscope just below the upper mirror and was adjusted to the size of the central bright spot of the beam from the laser.

Collimation of the source was beneficial to the pointing problem in that the beam could be centered at the receiver. To facilitate pointing without firing the laser, light from an auxiliary tungsten source was introduced into the laser periscope on axis by means of the beam splitter, as shown in Fig. 7. In addition to the narrow-band filter in the receiver, a similar filter was inserted in the laser periscope for the measurements, thereby increasing the rejection outside the passband by another factor of 10^6. It was removed for alignment checks.

The modification of the projection system required changes in the receiver optics. Since the receiver aperture would no longer be filled with light, the obscuration by the secondary mirror of the center portion of the incoming beam could not be tolerated. An entirely different optical system was substituted (Fig. 7) which consisted of a large compound lens, a narrow-band filter, and a 1/4-in. aperture. The lens was a Kodak Aero-Ektar, 12-in. focal length *f*/2.5 lens. The narrow-band filter was almost identical to the one in the laser periscope. A curve of the composite transmittance versus wavelength for the two filters for collimated light is shown in Fig. 8. The aperture was located at the focus of the lens and served to limit the diameter of the field of view to 1.2 degrees. The photocathode was located about 4 in. behind the aperture. The multiplier used this time was the same type as that used as a monitor, i.e., the infrared-sensitive type 6911.

One change was made in the data-taking process in an effort to improve accuracy. Instead of reading the peak deflections directly on the scope face, the trace of each pulse was photographed with a scope camera and the deflections were read from the photographs.

After exhaustive tests and thorough alignment of this system in the laboratory it was installed at the model basin. Great care was taken to position the periscopes accurately in all dimensions, i.e., laterally, in depth, and in plumb. The periscopes were pointed at each other over a 30-ft path and then the laser periscope was moved to

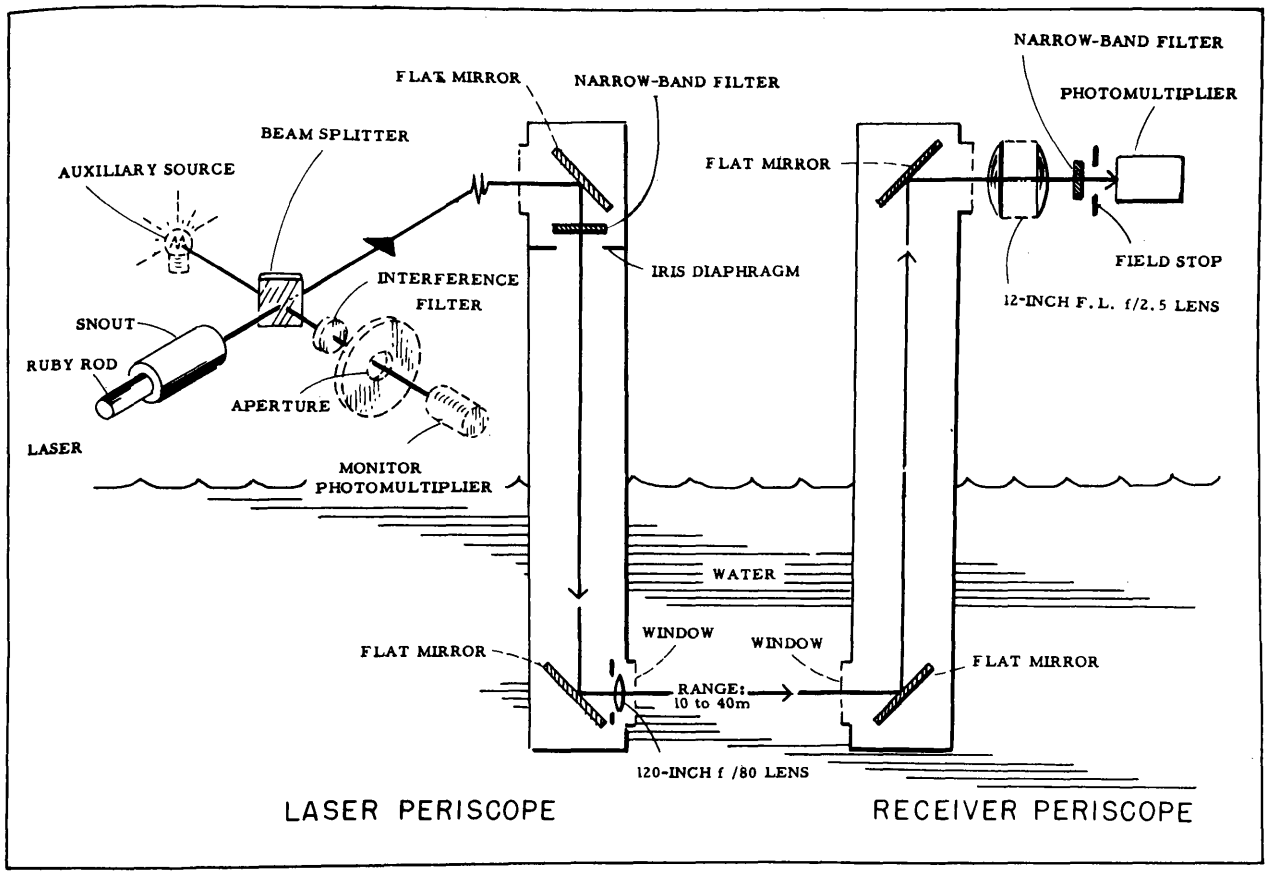

Fig. 7 - Schematic diagram of modified optical system

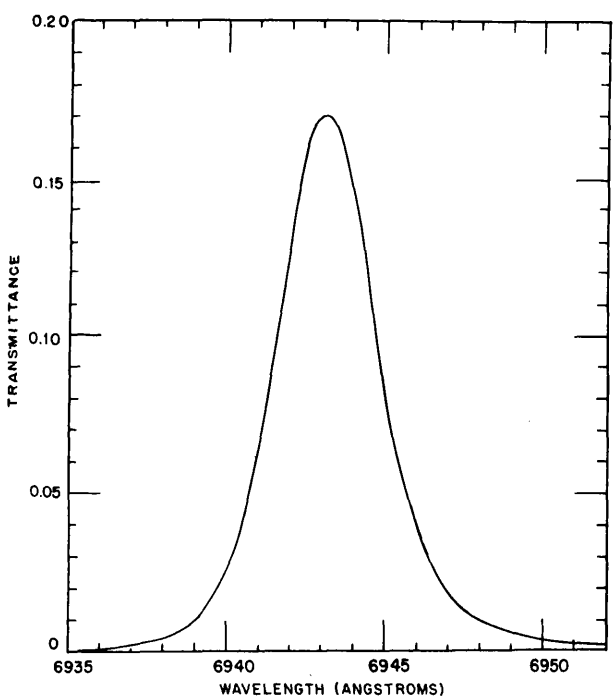

Fig. 8 - Curve of the composite transmittance of two laser light filters

100 ft. The correction in pointing required to bring the beam back to its original position at the receiver was one minute of arc.

Results

Measurements of the attenuation coefficient were made over water path lengths from 6.1 m to 36.6 m at intervals of 6.1 m. Two measurements were made at each distance, one with both narrow-band filters in the system and the other with only one of these filters. This was done to determine whether one filter was sufficient to get rid of scattered pump light in the long distance measurements. A typical oscilloscope trace of the pulse is shown in Fig. 9 in which the individual emission spikes are visible. The time scale is 200 μsec/cm.

The two resulting curves are shown plotted in Fig. 10. There is very little difference in the slopes; the values are −0.523 for the single filter and −0.545 for two filters. The resulting coefficient

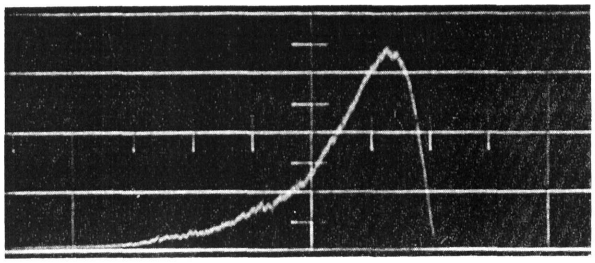

Fig. 9 - Typical oscilloscope trace of laser pulse (time scale is 200 μsec/div)

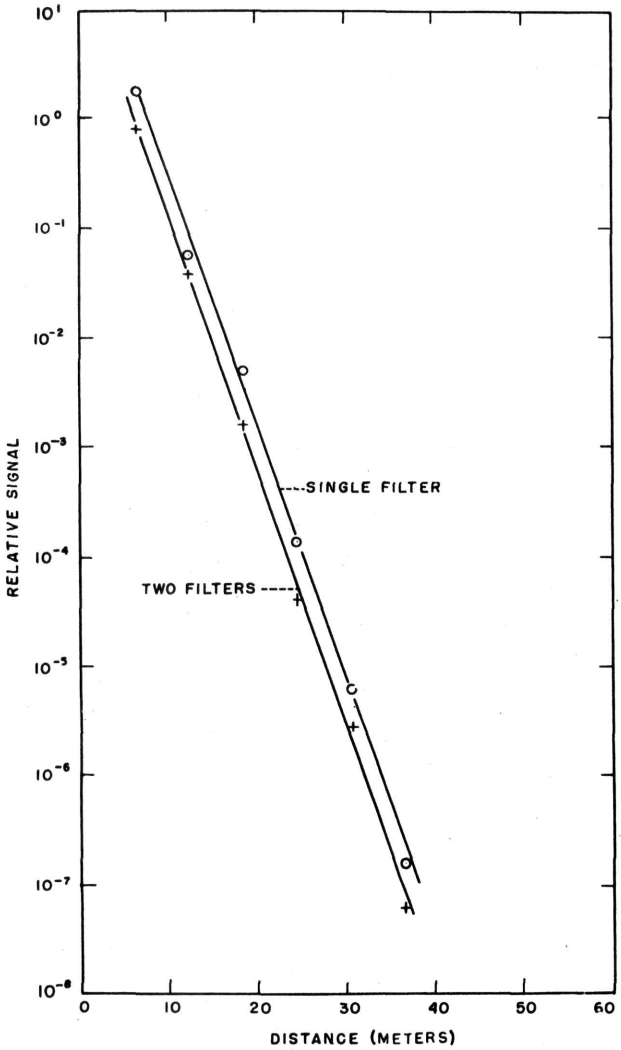

Fig. 10 - Relative transmissivity of Potomac River water at 6943A with one interference filter and with two filters

values are, therefore, 5.23×10^{-3} cm^{-1} and 5.45×10^{-3} cm^{-1}, respectively. Also, the latter value is within 3 percent of the value obtained with the initial optical setup, which was 5.3×10^{-3} cm^{-1}.

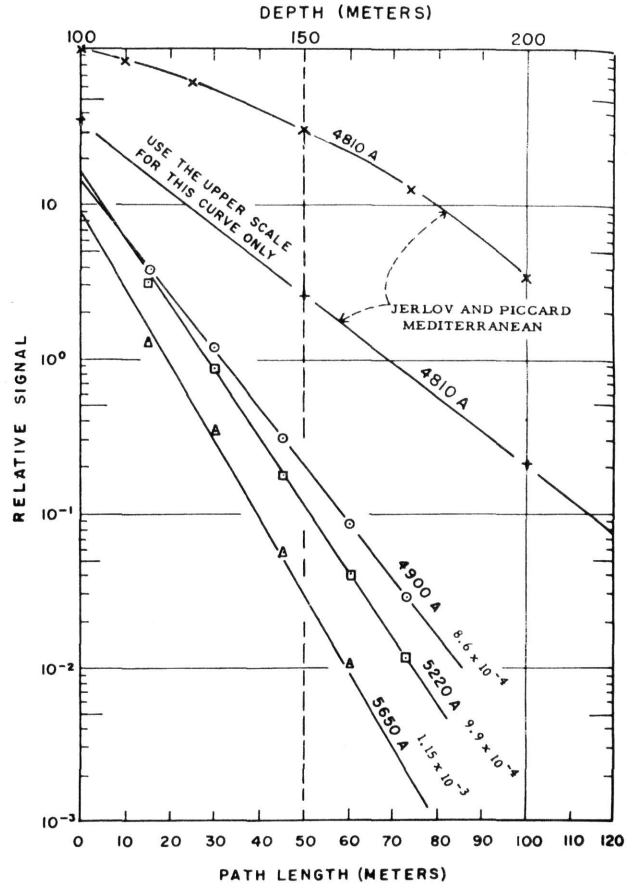

Fig. 11 - Relative transmissivity of Potomac River water at three green wavelengths as measured in the present investigation and of Mediterranean water as measured by Jerlov and Piccard. Attenuation coefficients shown on NRL data are in cm^{-1}

MEASUREMENTS WITH GREEN LIGHT

A further study of the attenuation characteristics of the water was made at three wavelengths in the green region. The only changes made in the system were the removal of the ruby rod, the replacement of the infrared multipliers with blue-sensitive type 6342 multipliers, and a change in the narrow-band interference filters.

Measurements began at 15.25 m and were made every 15.25 m to a maximum path length of 73.25 m. The three wavelengths were 4900A, 5220A, and 5650A. Two matched filters for each of these wavelengths were used for each measurement. The half bandwidth of the sets of two filters each were as follows: 48A at 4900A; 10A at 5220A; and 57A at 5650A.

The data obtained are shown plotted in Fig. 11, from which the values of the attenuation coefficients (Table 1, column 2) were obtained as in

the previous determination. Included in this figure for comparison is a portion of the curve obtained by Jerlov and Piccard (10) who studied the "extinction" of daylight by Mediterranean water at 4810A. The bandpass was 120A, or twice the widest bandwidth used in the present experiment. The optical arrangement included opal glass and a 20-degree acceptance angle, thus permitting the entrance of a varying amount of scattered light originating mainly in shallow depths where the density of scattering particles is normally greater. Although their observations extended to a depth of 300 m, only the portion of the curve between 0 and 200 m is shown here and is in two sections to conform to the scale of the ordinate. For the depth interval 100 to 300 m they quote a value for the absorption coefficient of 0.048 m^{-1}, which lies between the values for Potomac River water and distilled water. The relative clarity of Mediterranean water is attributed to low content of particulate matter and a fairly poor plankton population.

The NRL values shown in Fig. 11 were also plotted in Fig. 2 for comparison with the results of others. It may be noted that the relatively low attenuation indicated by the red measurement is confirmed by the three values in the green. The excess of attenuation above that of distilled water is undoubtedly caused by particulate scattering.

PARTICLE SCATTERING

Following the method used by Burt, an attempt has been made to obtain some information on scattering by the particles suspended in the basin water. As shown in Table 1 the measured coefficients were corrected for distilled water losses (Hulburt) so as to obtain the particle scattering.

The value at 6000A was interpolated from a smooth curve through the data, and the coefficient ratios in the last column were computed for use with working curves given by Burt, as shown in Fig. 12 for particulate matter found in the Chesapeake Bay. The ordinate in Fig. 12 is the effective cross section normalized at 6000A, as determined from the Mie scattering functions, and in this situation it is proportional to the scattering coefficient. Curves are shown for computed scattering coefficients for various particle radii as a function of wavelength and also for the data obtained in the present study. It can be seen at a glance that the data does not fit any of the curves which describe a monodisperse particle distribution. The curve shape strongly indicates that the particle size distribution remaining after filtering consists mainly of small particles of less than 0.4μ radius, with a small component of larger particles with radii greater than 1.0μ. More data are needed before the particle size distribution can be determined with assurance.

DISCUSSION

The attenuation of the basin water, which at first seemed low, now does not appear to be at all unusual. The fact that it approaches the attenuation of distilled water is not surprising considering that the basin water is continuously filtered. It is also to be expected that it would be clearer than the Pacific Ocean water (Ref. 8) which was taken close to shore and would therefore be expected to contain a large amount of particulate matter. The latter samples also were stored for a period of time, which reportedly can increase attenuation (11).

On the other hand, measurements of daylight penetration into the sea indicate there are locations where deep ocean water is comparable to distilled water. Jerlov and Piccard and others have obtained minimum attenuation coefficients with values between 0.033 and 0.039 m^{-1}, and Boden, Kampa, and Snodgrass (12) have reported values as low as 0.026 m^{-1}. The spread in coefficients for distilled water covers roughly the same values at the wavelength of the minimum, Hulburt's being the highest at 0.036 m^{-1}.

It is questionable whether the above comparison is meaningful because of the significantly different manner in which the observations were made, i.e., the geometry of both source and receiver in the sea penetration studies involved large angles, whereas in the present study the source and receiver used small angles.

If one assumed that the basin water is basically equivalent to distilled water with some suspended particulate matter, the data would indicate a distribution of mostly small particles of radii less than 0.4μ and a small percentage of larger particles with radii greater than 1.0μ.

The underwater range limit for the present laser and photomultiplier combination was computed for a S/N ratio of 1 and for two narrowband filters, but without any optical system except

TABLE 1
Values of Particle Scattering Coefficients Derived from Measured Attenuation Coefficients

Wavelength λ (angstroms)	Measured Coefficient (m^{-1})	Distilled Water Coefficient (m^{-1})	Particle Scattering Coefficient† (m^{-1})	Ratio $\sigma_\lambda/\sigma_{6000}$
4900	0.086	0.037	0.049	1.07
5220	0.099	0.041	0.058	1.26
5650	0.115	0.060	0.055	1.20
6000	0.243*	0.197	0.046	1.00
6943	0.545	0.513	0.032	0.70

*Interpolated.
†Column 2 − column 3.

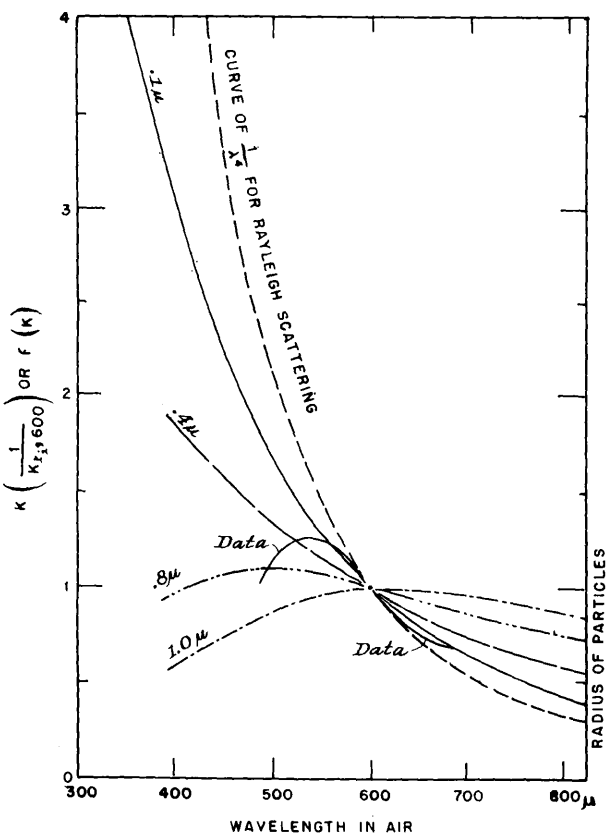

Fig. 12 - Curves of relative spectral scattering coefficients for various particle sizes in Chesapeake Bay water as given by Burt (Ref. 9)

the collimating lens. The signal at 36.6 m was 50 times greater than noise, and the estimated transmittance of the optical system was 0.35. Thus the additional range possible would be that equivalent to an attenuation of approximately 150 times which would be an additional 10 m of basin water, thus giving a maximum range of about 45 m.

The radiant energy of the laser in all observations was roughly 0.07 joule. The duration of the pulse measured at the half-power points was about 300 μsec, yielding a peak output power of slightly over 200 watts. It is interesting to consider the possibilities of *q*-switching in the problem. This process might be expected to increase the peak output power to 2×10^6 watts, or 10^4 times the normal output. In terms of underwater range, however, this amounts to an increase of only 17 m.

CONCLUSIONS

From the above observations it is rather obvious that a ruby laser is impractical as an underwater light source. The attenuation amounts to a factor of 10 every 4.2 m (14 ft) at 6943A in reasonably clear water. The limit of detection with the present source-detector combination is about 45 m. Even if the beam intensity of the laser were increased a billion times the range would only be doubled.

The situation is a little more advantageous at green wavelengths where the attenuation is at a minimum. Here a factor of 10 in attenuation occurs every 27 m (89 ft), or 10^9 in 250 m (820 ft), of filtered river water at 4900A. At 4600A through the clearest sea water ($\sigma = 0.026$ m^{-1}) mentioned

in the literature, an attenuation by a factor of 10 occurs every 88 m (290 ft), or 10^9 in 800 m (2600 ft).

ACKNOWLEDGMENTS

The authors wish to express their appreciation to LCDR C. H. Carroll of NRL for helping to arrange the use of the facilities of the David Taylor Model Basin (DTMB), to Mr. McGinley of DTMB for his cooperation in scheduling and other administrative details, to Kenneth Killian of DTMB for his assistance in the installation of equipment and in taking the data, to A. G. Rockman for the design of the periscope equipment and for aid in taking the data, to T. H. Cosden for help in taking the data, and to C. V. Acton for his photographic work and aid in the field.

REFERENCES

1. Hulburt, E.O., "Optics of Distilled and Natural Water," *J. Opt. Soc. Am.* **35**:698 (Nov. 1945)
2. Curcio, J.A., and Petty, C.C., "The Near Infrared Absorption Spectrum of Liquid Water," *J. Opt. Soc. Am.* **41**:302 (May 1951)
3. Drummeter, L.F., and Knestrick, G.L., "A High Resolution Investigation of the Spectral Attenuation Coefficients of Water," NRL Report 5642, May 1961
4. Burt, W.V., "Selective Transmission of Light in Tropical Pacific Waters," *Deep-Sea Res.* **5**:51 (1958)
5. Clarke, G.L., and Wertheim, G.K., "Measurements of Illumination at Great Depths and at Night in the Atlantic Ocean by Means of a New Bathyphotometer," *Deep-Sea Res.* **3**:189 (1956)
6. Clarke, G.L., and Backus, R.H., "Measurements of Light Penetration in Relation to Vertical Migration and Records of Luminescence of Deep-Sea Animals," *Deep-Sea Res.* **4**:1 (1956)
7. Kampa, E.M., and Boden, B.P., "Light Generation in a Sonic-Scattering Layer," *Deep-Sea Res.* **4**:73 (1956)
8. Mutschlecner, J.P., Burge, D.K., and Regelson, E., "Calibration and Laboratory Experiments with a Ruby Laser," U.S. Naval Ordnance Test Station Technical Note IDP-1485 (May 1962)
9. Burt, W.V., "Interpretation of Spectrophotometer Readings on Chesapeake Bay Water," *J. Marine Res.* **14**:47 (1955)
10. Jerlov, N.G., and Piccard, J., "Bathyscaph Measurements of Daylight Penetration into the Mediterranean," *Deep-Sea Res.* **5**:201 (1959)
11. Clarke, G.L., and James, H.R., "Laboratory Analysis of the Selective Absorption of Light by Sea Water," *J. Opt. Soc. Am.*, **29**:43 (1939)
12. Boden, B.P., Kampa, E.M., and Snodgrass, J.M., "Underwater Daylight Measurements in the Bay of Biscay," Scripps Inst. Oceanog. Contrib., New Series, No. 1164, p. 451 (1960)