Analytical and Experimental Evaluation of an Optical Fiber Ocean Mass Simulator

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Abstract— **High-power blue-green laser systems are utilized for analyzing ocean parameters and searching for underwater objects. Testing in surveying missions using such systems is time-consuming and expensive. Therefore, an experimental ocean mass simulator is needed to test and perfect new approaches for underwater detection. This simulator must include water effects of attenuation, absorption, and scattering on the transmitted optical pulse. By examining equations and experimental data relating the backscattered signal from optical fiber and from water, correlations are found which qualify the fiber as an efficient ocean mass simulator.**

I. Introduction

LIGHT detecting and ranging (LIDAR) is employed for tracking underwater objects and ocean bottom mapping. A typical system includes an aircraft with a high-power blue-green laser transmitter and an optical receiver. The optical signal, which is partially reflected from the water surface, is transmitted through the water, and is reflected from the ocean floor. As the transmitted optical signal propagates through the water medium, it is dispersed and attenuated due to absorption and scattering.

Conventional airborne LIDAR systems have coped with incoherent detection schemes, severely limiting their sensitivity. A hybrid lightwave-microwave technique has been proposed by Mullen [1] that can provide for coherent detection and, therefore, enhanced sensitivity. By modulating the light at microwave frequencies, an optical carrier with a microwave envelope is produced. In this scheme, the microwave radar signal is transported through the water by the optical carrier. Once the microwave envelope is recovered by a high-speed photodetector, it can then be subjected to well-established radar signal processing methods.

When considering this hybrid lightwave-microwave technique, it is important to determine the effect that water parameters will have on the modulated optical carrier. Since aerial surveying test methods are both costly and time-consuming, a simple, inexpensive experimental tool, an ocean mass simulator (OMS), is needed to empirically simulate the effects of the water on the propagating optical signal.

In this paper we report that backscattered light from plastic optical fiber exhibits characteristics that are remarkably similar to an aerial LIDAR return signal. Optical time domain reflectometry (OTDR) is used to examine this backscattered light and to determine fiber attenuation due to absorption and Rayleigh scattering, as well as scattering due to imperfections such as fiber breaks, bending, and splice discontinuities [2].

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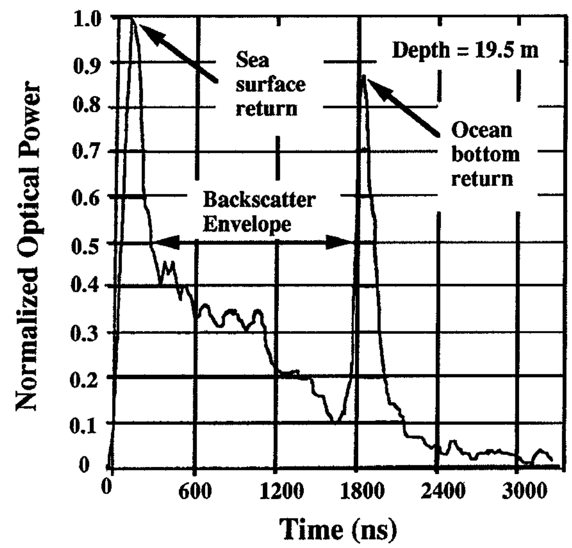

Fig. 1. Experimental waveform of a backscattered optical pulse from sea water from a laser hydrography system [3].

In this study, the backscattered optical power from water and from optical fiber are theoretically analyzed and compared. The theory is validated by experimental results which relate the attenuation characteristics of plastic fiber to specific Jerlov water types. The plastic fiber is, therefore, established as a simple, low-cost OMS.

II. Water and Optical Fiber Backscatter Characteristics

Two backscattered waveforms, one from a laser bathymetric system and one from an optical fiber, are depicted in Fig. 1 and Fig. 2, respectively. These similar waveforms are comprise1d of three components. The principal element of the signal is the backscatter envelope which is sandwiched between the surface and ocean bottom reflections (Fig. 1), or the fiber front and back reflections (Fig. 2).

In the water, the amplitude of the surface reflection varies with the height of the airplane, the angle of beam transmission and the turbidity of the water. If the water surface is dominated by waves, the surface reflection will change with consecutive transmitted laser pulses. Similarly, the fiber front fresnel

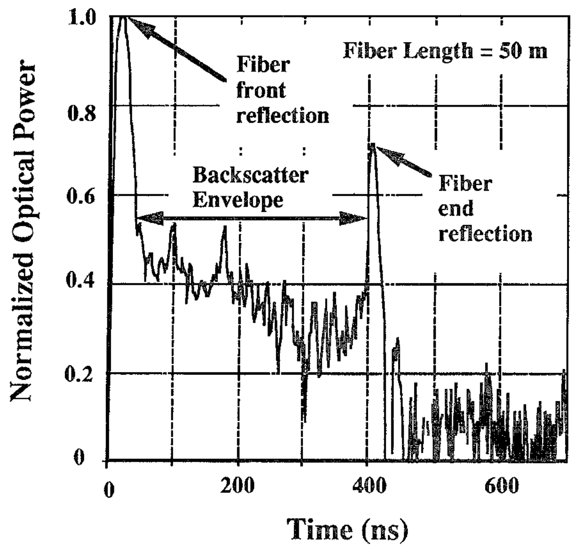

Fig. 2. Experimental waveform of a backscattered optical pulse from plastic optical fiber.

reflection is dependent on the angle of transmitted light, the distance between the source and the fiber, and the fiber surface. However, the fiber surface does not change between each transmitted pulse as is the case with water. Since the optical pulse disperses as it travels through water, the ocean bottom return is a distorted replica of the transmitted pulse. Upon examining the fiber end reflection, this equivalent pulse dispersion exists, but only in a very long fiber.

The main resemblance between the two signals lies in the backscatter envelope, which is dependent upon the properties of the propagation medium - the water or the fiber. In the water, scattering and attenuation results from suspended particles and underwater objects. In the fiber, Rayleigh scattering results from fiber impurities, while sharp peaks are caused by reflections from splices, breaks, and bends in the fiber. In the next sections, we examine and compare, analytically and experimentally, the attributes of the water and the fiber which govern the backscatter envelope.

III. Analysis Of Water And Fiber Backscatter

Jurand derived an analytical model of the total bathymetric waveform [4]. The impulse response for the backscatter of a pulse from a homogeneous water medium according to Jurand is

$$P_w(t) = \{[C_{atm}][C_{int}][\nu_w G_m \sigma(\pi)]\} e^{-K\nu_w t} \quad (1)$$

where C_{atm} represents atmospheric effects (i.e. height of airplane, attenuation of the atmosphere), and C_{int} describes the air-water interface conditions (incident angle, water transmission coefficient, water and air refractive indices). Also in (1), ν_w is the speed of light in the water and G_m is a correction factor relating backscattered energy and peak backscattered power in the water medium. The volume-scattering coefficient, $\sigma(\pi)$, is defined as the radiant intensity (from a volume element in a given direction) per unit of irradiance on the volume and per unit volume [5]. Here, the volume-scattering coefficient is evaluated only in the reverse (π) direction since we are concerned with the power backscattered to the receiver. The total attenuation coefficient, $K_a = K_{abs} + K_s$, is due to absorption (K_{abs}) and scattering (K_s). The diffuse attenuation coefficient, K, is defined as

$$K = K_a \left[\frac{1-\omega_0}{4}\right]^{\frac{\omega_0}{2}}, \quad (2)$$

where the single scattering albedo, $\omega_0 = K_s/K_a$, is the ratio of scattering to total attenuation [4]. Since we are primarily concerned with the effects of the water on the transmitted signal, the influence of the atmosphere (C_{atm}) and the air-water interface (C_{int}) in (1) is neglected. The terms of interest are $\sigma(\pi)$ and K, which classify water types as determined by Jerlov [5]. Specifically, for dirty water, the values of $K_a, \sigma(\pi)$, and ω_0 increase, while the reverse is true for clear water. These relationships cause the peak power and slope of the backscatter envelope to increase with dirtier water.

Now, for the optical fiber, the backscatter impulse response is [6]

$$P_F(t) = \left\{\frac{\nu_f}{2} S\alpha_s\right\} e^{\alpha\nu_f t}, \quad (3)$$

where ν_f is the velocity of light in the fiber. The parameter α_s is the Rayleigh-scattering loss in the forward direction, and is a function of the fiber length if the scattering is not isotropic. A fraction, S, of this scattered light propagates in the backward direction. The composite attenuation coefficient, α, is due to absorption, scattering, and other fiber losses.

In order to model different water types, we must be able to change the attributes of the fiber impulse response. One way of accomplishing this is to subject the fiber to different bending diameters. If the entire fiber is bent uniformly, reflections will occur due to the interaction of higher order modes with the core-cladding interface [7]. In addition, the light scattered in the backward direction, S, will be altered. Furthermore, loss of higher order modes to radiation will give rise to an attenuation coefficient which is a function of the bending diameter [7]. These effects will cause the peak backscattered power and fiber attenuation to increase as the bending diameter decreases.

If we rewrite (3) to include effects of bending, we have

$$P_F(t) = \left\{\frac{\nu_f}{2} R S_b \alpha_s\right\} e^{-\alpha_b \nu_f t}, \quad (4)$$

where R is the reflectivity, S_b is the fraction of scattered light in the backward direction and α_b is the attenuation coefficient, all functions of the bending diameter. Using (1) and (4), we can now compare the backscatter impulse response for the water and a homogeneous fiber. In (1), $G_m\sigma(\pi)$ describes the scattering of the light in the water, while in (4), $RS_b\alpha_s$ depicts the scattering and reflecting of the light in the fiber. Both of these parameters increase with either dirtier water or decreasing fiber bending diameter. The exponential term in each equation includes the attenuation characteristics of the light in either the water or the fiber. Again, this term increases with either dirtier water or sharper bending diameter.

To complete our study, we must discuss the differences between (1) and (4). First, we acknowledge the fact that the water is an unguided medium, while the fiber is a guided medium. Therefore, the proportion of scattered to transmitted

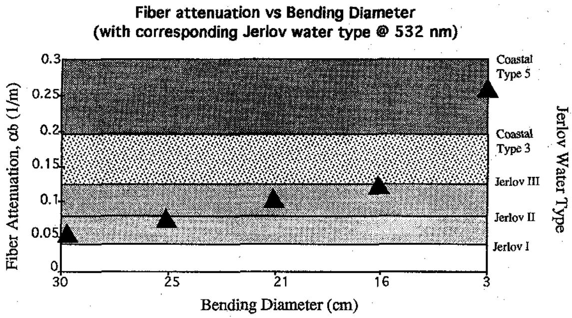

Fig. 3. Water types corresponding to fiber attentuation from varying bending diameters [8].

light in the water is less than in the fiber. In addition, the volume-scattering coefficient is considered specifically in the reverse direction in (1) as is the case with the fiber. The wavelength dependence of both K and α_b must also be studied. Each water type corresponds to certain values of K for different wavelengths. Therefore, when comparing the attenuation of the fiber to that of water, one must do so at a specific wavelength.

IV. Experimental Results

The backscattered signal from multimode plastic optical fiber was examined at 532 nm. Plastic optical fiber was utilized in this experiment since it transmits well in the blue-green wavelengths (as is with water), and it experiences a high degree of Rayleigh scattering, resulting in a greater backscatter signal. As the fiber was exposed to different uniform bending diameters, the attenuation varied as determined from the slope of the backscatter curve. The results shown in Fig. 3 reveal that these attenuations parameters correlate accurately with those resulting from specific water types.

V. Conclusion

In this study, we have introduced the need for an OMS to test application of the hybrid lightwave-microwave technique to LIDAR systems. To qualify optical fiber as an effective OMS, we have related the backscattered optical power from water and from fiber. We have shown, both theoretically and experimentally, that by changing the uniform bending diameter of optical fiber, different water types can be simulated. Thus, the optical fiber OMS will enable us to test the effect of the water on presently developed LIDAR techniques without the high cost of actual aerial surveying measurements.

References

[1] L. Mullen, *et al.*, "Fiber simulator for hybrid microwave-lightwave technology," *Digest, 11th Annual Benj. Frank. Symp. on Antenna and Microwave Tech. in the 1990s*, May 1993, pp. 3–6.

[2] M. K. Barnoski and S. M. Jensen, "Fiber waveguides: a novel technique for investigating attenuation characteristics," *Applied Optics*, vol. 15, no. 9, pp. 2112–2115, Sept. 1976.

[3] B. Billard and P. J. Wilson, "Sea surface and depth detection in the WRELANDS airborne depth sounder," *Applied Optics*, vol. 25, no. 13, pp. 2059–2066, 1986.

[4] T. P. Jurand, "Analytical model for optical pulse propagation in aerial bathymetr ic surveying," *Ph.D. Dissertation*, Drexel University, Philadelphia, PA, 1991.

[5] N. G. Jerlov, *Optical Oceanograpy*, vol. 5., Amsterdam: Elsevier Publishing, 1968.

[6] S. D. Personick, "Photon probe—an optical-fiber time-domain reflectometer," *The Bell System Technical Journal*, vol. 56, no. 3, pp. 355–366, March 1977.

[7] D. Gloge, "Bending loss in multimode fibers with graded and ungraded core index," *Applied Optics*, vol. 11, no. 11, Nov. 1972.

[8] Pacific-Sierra Research Corporation, Technical Memorandum: "Spectral transmission of light through seawater," Sept. 15, 1992.