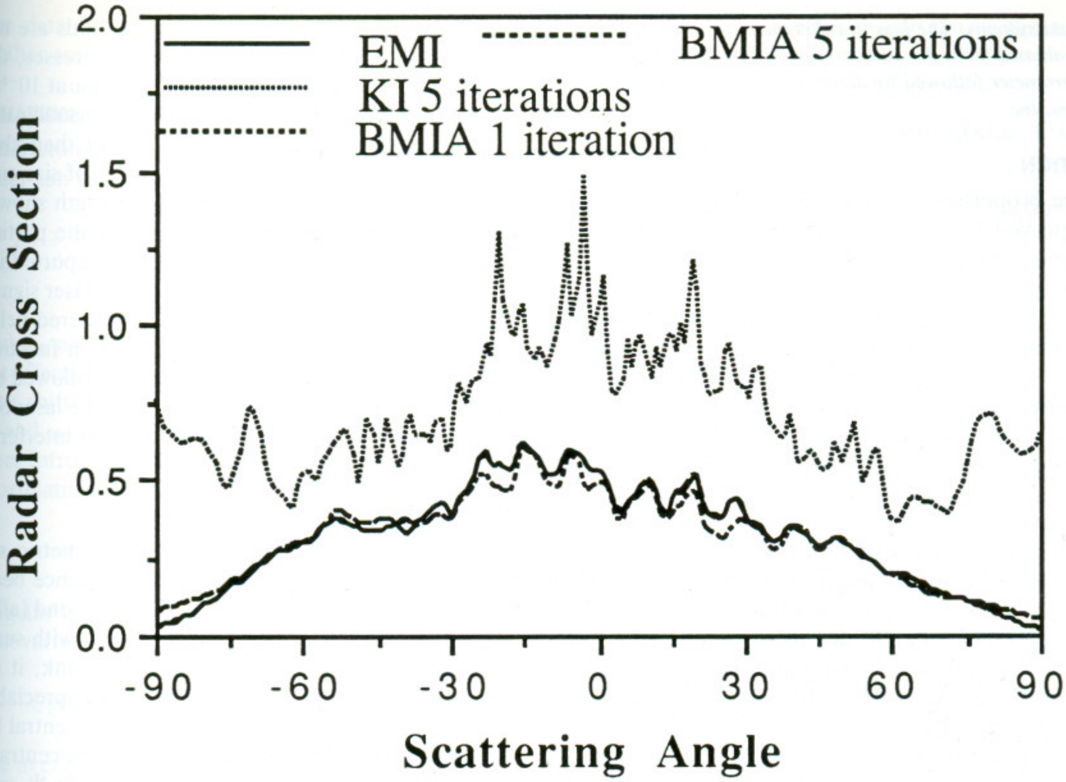

Figure 3 Radar cross section versus scattering angle for Case 2 after 100 realizations

TABLE 1 Comparison of CPU Seconds on a vax-6000-350

	Matrix Inversion	BMIA One iteration	BMIA Five iterations	KI Five iterations
Case 1	23.16	0.98	2.07	1.52
Case 2	22.94	0.92	2.05	1.59

cident angle is 20° from normal. Figure 1 shows the comparison of total field on the rough surface for Case 1 for a single realization; both BMIA and KI agree well with EMI after five iterations. It should be noted that BMIA is more accurate than KI at the two edges of the surface. Figures 2 and 3 show the ensemble average of 100 realizations of radar cross section of the rough surface for Cases 1 and 2, respectively. For Case 1, BMIA agrees very well with EMI after five iterations. Both BMIA with one iteration and KI with five iterations give the general trend of the EMI. Backscattering enhancement is observed. Thus the first-order solution of BMIA already gives backscattering enhancement. For Case 2, however, both BMIA with both one and five iterations agrees very well with EMI when KI yields erroneous results. The CPU time for solving the matrix equation using EMI, BMIA, and KI is listed in Table 1. It is shown that BMIA is much faster than EMI and is comparable to KI. BMIA continues to work when KI fails.

REFERENCES

1. R. M. Axline and A. K. Fung, "Numerical Computation of Scattering from a Perfectly Conducting Random Surface," *IEEE Trans. Antennas Propagat.*, Vol. AP-26, 1978, pp. 482–488.
2. J. S. Chen and A. Ishimaru, "Numerical Simulation of the Second Order Kirchoff Approximation from Very Rough Surfaces and Study of Backscattering Enhancement," *J. Acoust. Soc. Am.*, Vol. 88, 1990, pp. 1846–1850.
3. A. A. Maraudin, T. Michel, A. R. McGurn, and E. R. Mendez, "Enhanced Backscattering of Light from a Random Grating," *Ann. Phys. (N.Y.)*, Vol. 203, 1990, pp. 255–307.
4. D. J. Wingham and R. H. Devayya, "A Note on the Use of the Neumann Expansion in Calculating the Scatter from Rough Surfaces," *IEEE Trans. Antennas Propagat.*, Vol. AP-40, 1992, pp. 560–563.
5. S. H. Lou, L. Tsang, C. H. Chan, and A. Ishimaru, "Application of the Finite Element Method to Monte Carlo Simulations of Scattering of Waves by Random Rough Surface with the Periodic Boundary Conditions," *J. Electromagn. Waves Appl.*, Vol. 5, 1991, pp. 835–855.
6. A. Ishimaru, "Wave Propagation and Scattering in Random Media and Rough Surfaces," *Proc. IEEE*, Vol. 79, 1991, pp. 1359–1366.

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MEASUREMENT OF THE TEMPORAL COHERENCE OF AN UNDERWATER OPTICAL SCATTERED FIELD

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KEY TERMS

Temporal coherence, scattering, heterodyning

ABSTRACT

The coherence of a laser signal propagating through a turbid medium deteriorates due to scattering, affecting the performance of un-

derwater coherent systems. The loss in coherence due to the scattering has been evaluated from the autocorrelation function obtained with an interoferometer followed by digital signal processing.

I. INTRODUCTION

The coherence properties of narrow spectral linewidth laser signals have proved to be of great importance in imaging, communications, optical sensing, and measurements. However, for applications in a medium with suspended particles, such as ocean waters, the coherence characteristics change due to the scattering of light, impairing the performance of optical systems. Image processing techniques based on the difference between the temporal coherence of the unscattered laser signal and the strong background illumination including scattered signal can achieve a large degree of image enhancement [1].

The laser beam in line-of-sight propagation is always a mixture of the incident and scattered light. The total field is almost coherent for a short distance from the transmitter since scattering is significant. At a greater distance, however, the total field becomes less coherent due to scattering, although the field collected at a narrow receiving angle is predominantly coherent. At a large distance, when the main beam has been significantly attenuated due to scattering and absorption, the total field approaches total incoherence. Both singly and multiply scattered radiation is of importance for optical systems in which the transmitter and receiver are widely separated. The actual amount of received forward-scattered power depends on the properties of the medium, receiver area, angular field of view, and the beam characteristics.

To assist in characterizing the coherence properties of a laser beam, the instantaneous scattered field can be regarded as the superposition of waves scattered from the individual scattering centers. This scattered field therefore fluctuates in response to the motion of the scatterers. The detection method used in a particular experiment depends on the time scale of these fluctuations. Filter methods are used to study relatively rapid molecular dynamic processes, that is, those that occur on a time scale faster than about 10^{-6} sec. Optical mixing or heterodyning methods are usually used for processes that occur on time scales slower than about 10^{-6} sec [2]. The scattered signal from particles of size comparable to or larger than the laser signal wavelength shows a Doppler effect due to the Brownian motion of the particles and turbulence in ocean waters. In the study reported in this article the coherence times of the unscattered laser signal along with the scattered field, and that of the scattered field only, have been evaluated from the autocorrelation function, obtained using a Mach-Zehnder interferometer followed by digital signal processing. The coherence time of the laser beam has also been measured in air using a Michelson interferometer [3].

II. EXPERIMENTAL PROCEDURE

The modified Mach-Zehnder interferometric system is arranged as shown in Figure 1. The reference beam is shifted by Ω and propagates through air. The second (affected beam) propagates through a 1.2-m water path with suspended particles. As the affected team exits the tank, it contains two parts: (1) a central beam without any appreciable scattering and (ii) the scattered signal around this central beam. In the first experiment both the parts (that is, the central unscattered beam plus the scattered light up to angle $\Psi = 2.4°$ off the optical axis) are collected by a lense and heterodyned with the reference beam using a photomultiplier tube that provides current output signal proportional to the light intensity. In the second experiment, the central beam is blocked and only the scattered light is collected and heterodyned with the reference beam.

The heterodyned output current is connected to a digital oscilloscope that provides a convenient means for digitizing the current signal. The signal is digitized into 1028 sample points at 8-bit resolution and is stored in the oscilloscope

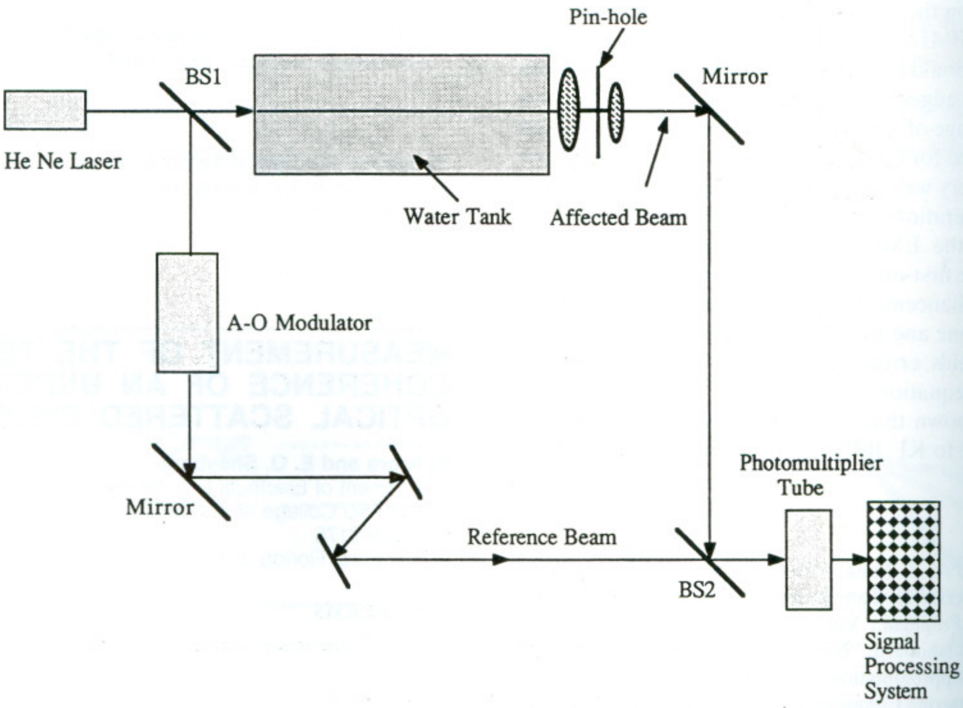

Figure 1 Mach-Zehnder interferometer

memory. The data from the digital oscilloscope are transferred to another computer for further signal processing.

III. DETERMINATION OF COHERENCE TIME

Using the interferometric system the output current of the photomultiplier can be expressed as

$$i_d(t) = E_1^2 + E_2^2 + 2E_1E_2 \cos[(\Omega - \omega_D)t + \Theta_r(t) - \Theta_w(t)], \quad (1)$$

where E_1 and E_2 are the field amplitudes of the reference beam and the affected beam, respectively, Θ_w and Θ_r are the random phase shifts of the affected and reference beams, respectively, and ω_D is the random frequency shift due to the Doppler effect introduced by the water path [4]. The estimated autocorrelation function is

$$R(\tau) = \langle i_d(t + \tau) i_d^*(t) \rangle, \quad (2)$$

where the angular brackets indicate time averaging. The estimated autocovariance from Eq. (2) is

$$C(\tau) = \langle i_d(t + \tau) i_d^*(t) \rangle - \overline{i_d^2}, \quad (3)$$

where $\overline{i_d^2}$ is the average value of the square of the current $i_d(t)$ over the time interval of interest.

The random Doppler shift due to turbulence and the Brownian motion of the suspended particles, ω_d, is assumed to have a Gaussian probability density distribution with variance σ^2. The variance σ^2 is a function of wavelength of radiation, path length, medium quality, temperature, and turbulence conditions, etc. Also in Eq. (1), assuming $\Theta_r \approx \Theta_w \approx 0$, it can be shown that the autocovariance function is Gaussian and is expressed as

$$C(\tau) = E_1^2 \cdot E_2^2 \cos(\Omega\tau) \exp(-\sigma^2\tau^2/2) = C_e(\tau) \cos(\Omega\tau), \quad (4)$$

where $C_e(\tau)$ is the envelope of $C(\tau)$.

The coherence time is defined as [2]

$$\tau_C = \int_0^\infty \frac{C_e(\tau)}{C_e(0)} \, d\tau. \quad (5)$$

Substituting Eq. (4) into Eq. (5) and simplifying.

$$\tau_C = 1.25\, \sigma.$$

The value of the covariance function envelope $C_e(\tau)$ at τ_c is

$$C_e(\tau = 1.25\sigma) = 0.456 C_e(0). \quad (6)$$

This shows that the coherence time τ_c corresponds to the time at which the envelope of the covariance function is 0.456 of its peak value $C(\tau = 0)$. To compute $C(\tau)$ from experimental values of i_d over a time T, i_d is sampled and stored as N discrete values. Thus, the sampling interval is $\Delta t = T/N$, and the sample time can be expressed as $t = n\,\Delta t$, where n is an integer index ranging from 0 to $N - 1$. The discrete correlation parameter τ can similarly be expressed as $k\,\Delta t$, where k is an integer index. With this notation and converting the integral to a sum, the autocorrelation function in discrete form is

$$R(k\,\Delta t) = \frac{1}{N} \sum_{n=0}^{N-1} i_d(n\,\Delta t) \cdot i_d(n\,\Delta t + k\,\Delta t). \quad (7)$$

The corresponding autocovariance function in discrete form is

$$C(k\,\Delta t) = R(k\,\Delta t) - \frac{1}{N} \sum_{n=0}^{N-1} i_d^2(n\,\Delta t). \quad (8)$$

Using this equation the covariance function is computed and graphed. The coherence time τ_c is computed based on Eq. (6) using an extrapolation technique.

IV. EXPERIMENTAL DATA AND RESULTS

Measurements of the heterodyned output current for determining the autocorrelation function were made with $\Omega = 80$ MHz, $T = 20$ nsec, and $N = 1028$. The index k in Eq. (8) is arbitrary but must be chosen such that $k_{\max}\,\Delta t \ll N\,\Delta t$ or $k_{\max} \ll N$. A value of $K = 100$ was used. The calculated autocorrelation functions for the scattered signal only, and the scattered field plus the central laser beam, are graphed in Figures 2(a) and 3(a), respectively. The corresponding autocovariance functions are graphed in Figures 2(b) and 3(b). The peak value of autocovariance function, $C(0)$, is the calculated value for $k = 0$. This value is multiplied by 0.456 to establish the value at which τ_c is to be determined. Since the time corresponding to $0.456C(0)$ may not align with a $k\,\Delta t$, it is necessary to perform an interpolation between the two nearest $k\,\Delta t$ points. The computed values of coherence time τ_c and length l_c are tabulated in Table 1. For comparison the

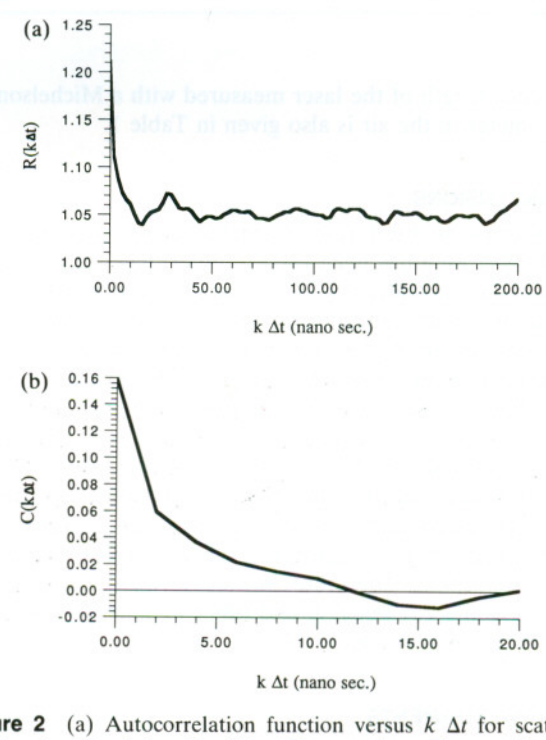

Figure 2 (a) Autocorrelation function versus $k\,\Delta t$ for scattered signal only. Signal duration $T = 20$ μsec, $\Delta t = 2$ nsec. (b) Autocovariance function versus $k\,\Delta t$ for scattered signal only. Signal duration $T = 20$ μsec, $\Delta t = 2$ nsec

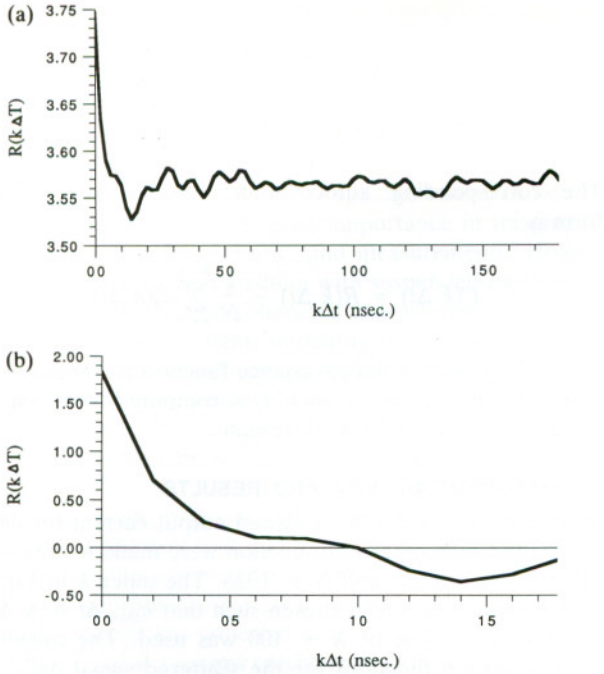

Figure 3 (a) Autocorrelation function versus $k\ \Delta t(\tau)$ for scattered signal plus direct laser beam. Signal duration $T = 20\ \mu$sec, $\Delta t = 2$ nsec. (b) Autocovariance function versus $k\ \Delta t(\tau)$ for scattered signal plus direct laser beam. Signal duration $T = 20\ \mu$sec, $\Delta t = 2$ nsec

TABLE 1 Coherence Time and Coherence Length

Only Scattering		Direct Beamscattering		Laser Signal (Michelson Interferometer)	
τ_c (nsec)	l_c (cm)	τ_c (nsec)	l_c (cm)	τ_c (nsec)	l_c (cm)
1.6	48	1.9	57	≈9.0	≈270.0

coherence length of the laser measured with a Michelson interferometer in the air is also given in Table 1.

V. CONCLUSIONS

In this article an interferometric technique followed by digital signal processing has been used to determine the loss in coherence due to scattering in simulated ocean waters. Comparing the results tabulated in Table 1, it is noted that the coherence length of the laser signal in air as measured using a Michelson interferometer is on the order of 270 cm. In a water medium, the coherence length of the scattered signal reduces to ≈48 cm, whereas the coherence length of scattered plus unscattered signal is between these two values. This is to be expected, since the direct unscattered beam contributes to the collected light and has greater coherence length. Clearly, scattering through water has a significant effect on coherence length. Therefore, the design of underwater coherent systems for imaging and other applications needs to consider the loss in coherence.

ACKNOWLEDGMENTS

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REFERENCES

1. D. Hickman and C. J. Duffy, "Incorporation of Imaging into a Temporal Coherence Sensor," *Opt. Lett.*, Vol. 13, Oct. 1988, pp. 898–900.
2. B. J. Berne and R. Pecora, *Dynamic Light Scattering*, Wiley, New York, 1976.
3. N. L. Swanson, "Coherence Loss of Laser Light Propagating Through Simulated Coastal Waters," in *Proceedings of the SPIE Ocean Optics XI Conference*, 1992.
4. T. J. Harrison, K. Arora, and N. K. Mitchell, "Effect on Spectral Properties and Attenuation of a Laser Beam Propagating Through Water," Technical report, Contract No. N61331-89-M-4413, FAMU/FSU College of Engineering, March 1990.

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ERRATA "VERNIER FIBER DOUBLE-RING RESONATOR USING DEGENERATE TWO-WAVE MIXING"

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There are a few typographical errors in Reference [1]. The right-hand side of Eq. (1) should be multiplied by a_1^2, that of Eq. (2) by a_2^2, and that of Eq. (4) by a^4. In Eqs. (6) and (7), t_1 should read t_i.

REFERENCE

1. Y. H. Ja, "Vernier Fiber Double-Ring Resonator Using Degenerate Two-Wave Mixing," *Microwave Opt. Technol. Lett.*, Vol. 5, 1992, pp. 181–183.

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ERRATA "CALCULATION OF *S* PARAMETERS FROM ABCD PARAMETERS WITH COMPLEX NORMALIZING IMPEDANCES"

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The above article [1] appears with three typographical errors. On page 613, the equation for V_{ji} should read

$$V_{ji} = a_j \cdot Z_{0j}^* \cdot \left[\frac{2}{Z_{0j} + Z_{0j}^*}\right]^{1/2}$$