Investigation of Modulated Laser Techniques for Improved Underwater Imaging

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LONG-TERM GOALS

The ultimate goal of this program is to determine the benefits and limitations of using modulated optical signals to image underwater objects and to compare this approach with existing underwater imaging techniques.

OBJECTIVES

The objective of this program is to investigate the application of modulated laser techniques to improve the contrast and resolution of underwater imaging systems. Specifically, the goals of the program are as follows:
1.   To determine how the optical properties of water affect the propagation of a modulated optical signal.
2.   To quantify under what conditions (i.e., system configuration, water quality, object characteristics) this approach improves underwater imaging.
3.   To compare this approach with more traditional laser imaging systems, such as laser line scanner and range-gated systems.

APPROACH

This project will focus on the theoretical and experimental analysis of modulated laser approaches for improving underwater imaging. Tools developed in a previous program ("Application of Hybrid Lidar-Radar Technology to a Laser Line Scanner") will be used to determine the effect of water optical properties and system characteristics on the propagation of a modulated optical signal in water. The general approach will be to carefully measure the optical properties of the water (scattering and absorption) and characterize the system components (optical receiver, modulated laser transmitter, target properties), use these variables as inputs to a theoretical model, and use the model to determine how the contrast and resolution of an image is affected by the modulation. Dr. Eleonora Zege at the National Academy of Sciences, Belarus, developed the fundamental theory needed for this model. A user-friendly computer simulation that incorporates this theory has been developed so that the various inputs (water optical properties, system characteristics, target geometry) can be easily varied to determine the effect on the modulated system performance. Concurrent with the modeling effort, experiments have been performed and the data has been compared to the theoretical predictions. In both the model and experimental results obtained in FY02, maxima and minima were observed in the

Report Documentation Page		

1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE	3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **Investigation of Modulated Laser Techniques for Improved Underwater Imaging**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **NAVAIR, EO and Special Mission Sensors,,Division 4.5.6, Building 2185 Suite 1100-A3,,22347 Cedar Point Road Unit 6,,Patuxent River,,MD, 20670**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **The ultimate goal of this program is to determine the benefits and limitations of using modulated optical signals to image underwater objects and to compare this approach with existing underwater imaging techniques.**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

dependence of signal power on the modulation frequency. A detailed investigation into the origin of these fluctuations was conducted in FY03 to better understand their effect on system performance.

WORK COMPLETED

The first task completed was the development of a program, Modulated Vision System (MVS), that simulates the performance of underwater, modulated laser imaging systems. Controlled laboratory tank experiments were conducted in FY02 to validate the MVS program results for a fixed set of system and environmental parameters. It was observed in both experimental and computer simulation results that under certain conditions, maxima and minima were observed in the dependence of signal power on the modulation frequency. A preliminary explanation for these results was that the reflection of the modulated optical signal from the target interacted with the backscatter signal to produce both constructive and destructive interference of the modulation envelope at the receiver. The focus of the work completed in FY03 was to better understand and explain these interference effects and their influence on the images created by a modulated laser imaging system. The MVS program was used to study the relationships between the amplitude and phase of the target and backscatter signals and to determine under what circumstances they produced constructive, destructive, or no interference. The experimental data was also examined in more detail to test the hypotheses generated by the model analyses.

Another task completed in FY03 was the design and development of a compact, single modulation frequency (70MHz) system for AUV platforms. This work was initiated due to collaboration with researchers from the Scripps Institute of Oceanography to study the potential for using the modulated laser approach in an AUV-mounted, underwater laser imaging system. The system was assembled with off-the-shelf components and is currently being tested in a water tank at NAVAIR.

RESULTS

In the modulated imaging system, the total power detected by the optical receiver with its axis directed to any point $\mathbf{r}$ at the object plane $z = 0$, $P(\mathbf{r},t)$, is a sum of the valid signal from an underwater object, $P_{VS}(\mathbf{r},t)$, and the backscatter signal from water, $P_{BSN}(\mathbf{r},t)$:

$$P(\mathbf{r},t) = P_{VS}(\mathbf{r},t) + P_{BSN}(\mathbf{r},t). \tag{1}$$

The valid target signal and backscatter signal are expressed as

$$P_{VS}(\mathbf{r},t) = P_{VS}(\mathbf{r}) \exp[i\,(2\pi f t - \varphi_{VS}(\mathbf{r}))], \text{ and} \tag{2}$$

$$P_{BSN}(\mathbf{r},t) = P_{BSN}(\mathbf{r}) \exp[i\,(2\pi f t - \varphi_{BSN}(\mathbf{r}))] \tag{3}$$

where $P_{VS}(\mathbf{r})$, $P_{BSN}(\mathbf{r})$ are the amplitudes and $\varphi_{VS}(\mathbf{r})$, $\varphi_{BSN}(\mathbf{r})$ are the phases of the valid target signal and the backscatter signal, respectively at modulation frequency, f.

To understand and explain the interference effects observed in simulation and experimental data and their influence on the images created by a modulated laser imaging system, the following relationships were studied in detail: 1) the dependencies of the backscatter noise phase and amplitude, $\varphi_{BSN}(z,f)$ and $P_{BSN}(z,f)$, and the valid signal phase and amplitude, $\varphi_{vs}(z,f)$ and $P_{VS}(z,f)$, on the modulation frequency, f, at a specific depth, z, and at $\mathbf{r}$=0; and 2) the dependencies of $\varphi_{BSN}(\mathbf{r})$, $P_{BSN}(\mathbf{r})$, $P_{VS}(\mathbf{r})$, and $\varphi_{vs}(\mathbf{r})$ on the coordinate $\mathbf{r}$ at the image plane. A figure of merit for quantifying

the effect of the backscatter and the valid signals on the system sensitivity is the contrast of the target at the target center (at **r**=0):

$$k(z,f) = \frac{P(z,f) - P_{BSN}(z,f)}{P(z,f) + P_{BSN}(z,f)} \tag{4}$$

where $P(z,f)$ and $P_{BSN}(z,f)$ are the powers of total signal and the backscatter signal at the center of the target at depth z and modulation frequency f, respectively. To determine the effect of the relationships between the relative phase, $\varphi = \varphi_{BSN}(z,f) - \varphi_{vs}(z,f)$, and the amplitude ratio, $\eta = P_{BSN}(z,f)/P_{VS}(z,f)$, on the target contrast, $k(z,f)$, the two extreme points, where the phase shift between the backscatter and valid signals is equal to $\varphi = 0$ or $\varphi = \pi$, was examined in detail.

Case 1: $\varphi = \varphi_{BSN}(z,f) - \varphi_{vs}(z,f) = 0$. When the phases of the backscatter and valid signals are equal (or a multiple of 360 degrees), constructive interference occurs:

$$k_{constr} = \frac{|P_{VS}|}{|P_{VS}| + 2|P_{BSN}|} = \frac{1}{1 + 2\eta}. \tag{5}$$

In this case, the contrast is positive ($k_{constr} > 0$) for any η. The value of η decreases and the contrast k_{constr} grows with decreasing depth, increasing modulation frequency or decreasing beam attenuation.

Case2: $\varphi = \varphi_{BSN}(z,f) - \varphi_{vs}(z,f) = \pi$. When the two signals are opposite in phase (odd multiples of 180 degrees), destructive interference occurs. Two situations are possible in this case:

1. When $|P_{BSN}| < |P_{vs}|$ (i.e. $\eta < 1$), the contrast corresponding to destructive interference becomes:

$$k_{destr} = \frac{|P_{VS}| - 2|P_{BSN}|}{|P_{VS}|} = 1 - 2\eta. \tag{6}$$

Equation (7) shows that the contrast $k_{destr} > 0$ at $\eta < 0.5$, which would occur at shallow depths or in clear water when the valid target signal is large and/or for high modulation frequencies when the backscatter signal is strongly decorrelated. The negative contrast $k_{destr} < 0$ is produced when $\eta > 0.5$, which requires comparatively large depths, more turbid water, and/or low modulation frequencies.

2. When $|P_{BSN}| > |P_{vs}|$ (i.e. $\eta > 1$), the contrast corresponding to destructive interference is:

$$k_{destr} = \frac{|P_{VS}|}{2|P_{BSN}| - |P_{VS}|} = -\frac{1}{2\eta - 1}. \tag{7}$$

In this case, the contrast k_{destr} is negative for any $\eta > 1$.

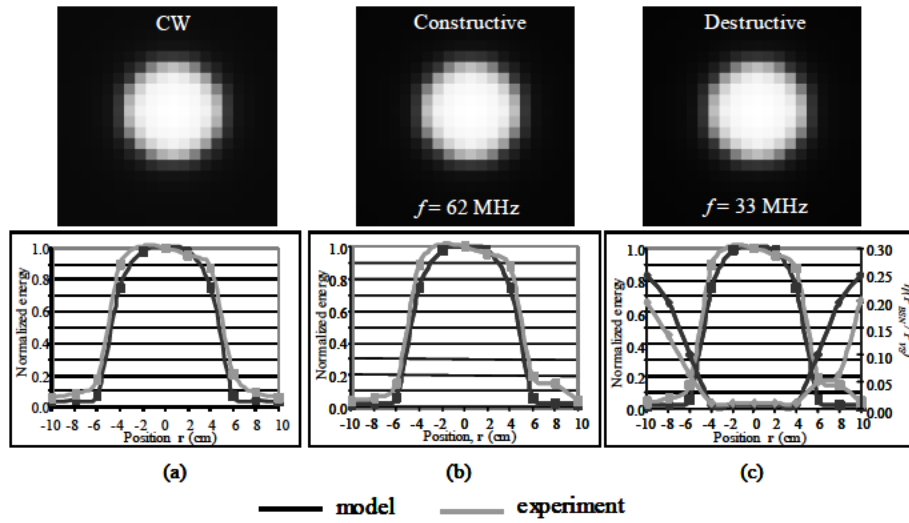In summary, when $\varphi = \varphi_{BSN}(z,f) - \varphi_{vs}(z,f) = \pi$,

$$k_{destr} > 0 \quad \text{at} \quad \eta < 0.5 \quad \text{and} \quad k_{destr} < 0 \quad \text{at} \quad \eta > 0.5. \tag{8}$$

Results from the MVS program and laboratory tank experiments are shown in Figure 1 to illustrate the effect of the phase and amplitude differences between the backscatter and target signals on the target contrast. These results were obtained with a receiver field of view of 1 degree and a source-receiver separation of 0.289m. Other details of the experimental setup can be found elsewhere[1,2]. For the cleanest water (c=1.2/m), both the experiment and the model show high contrast that is relatively independent of modulation frequency. However, for c=2.1/m and 2.5/m, the contrast shows evidence of constructive and destructive interference effects. The corresponding phase data in Figure 1b show that the location of contrast minima and maxima (indicated by dashed lines) correlate with the conditions when $\varphi = 180$ and $\varphi = 360$, respectively. The agreement between the model and the experiment is quite good, especially at modulation frequencies exceeding 50MHz.
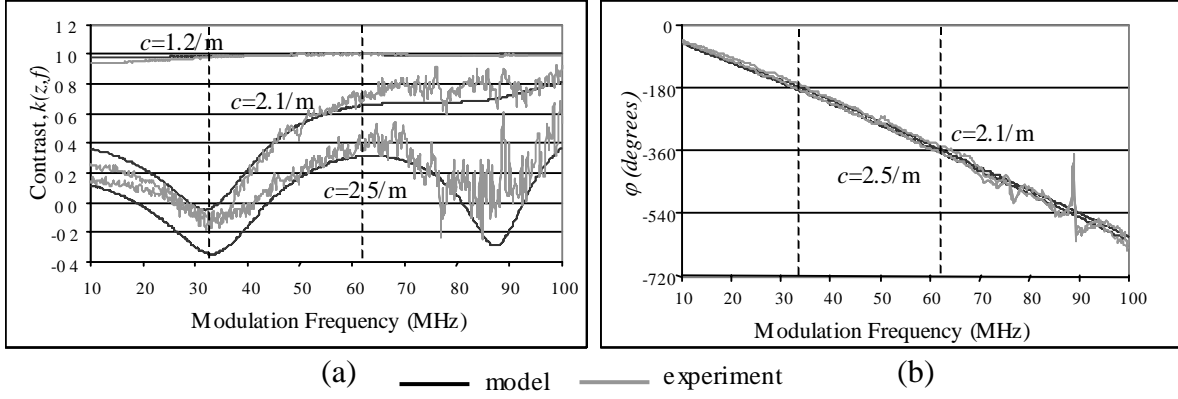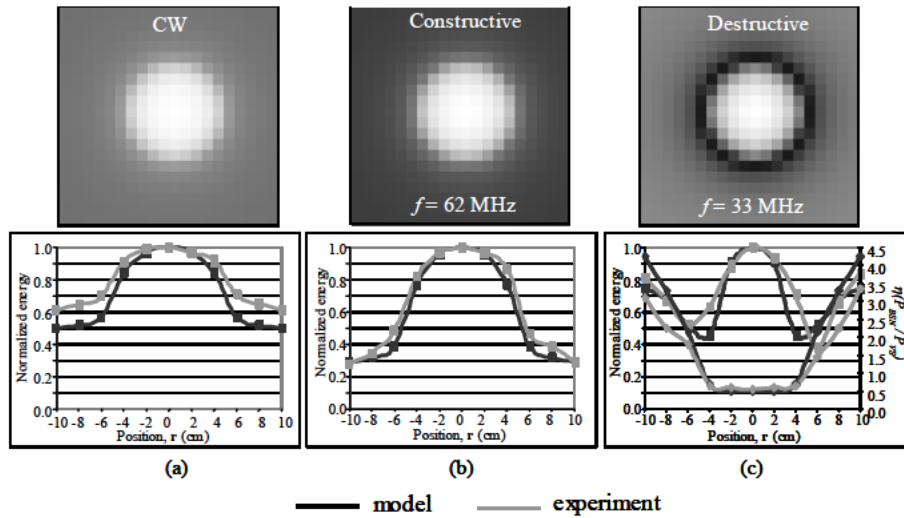
Figure 1. Target contrast (a) and corresponding backscatter-target phase difference (b) as a function of modulation frequency for a target depth=2.74m.

The effect of these variances in target contrast on the images produced by the modulated vision system can be better understood by studying the dependence of the backscatter and valid signal phases on the spatial coordinate **r** in the target plane. The cross-sectional images corresponding to the data in Figure 1 are shown in Figures 2-4 where the 'Constructive' and 'Destructive' images are those obtained with a modulation frequency corresponding to $\varphi = 360$ and $\varphi = 180$, respectively. The 2-D images produced by the MVS program are also shown for reference, as is the 'CW' (no modulation) image. In the 'Destructive' image graphs, the value of the amplitude ratio between the backscatter and valid signals, $\eta(\mathbf{r})=P_{BSN}(\mathbf{r})/P_{vs}(\mathbf{r})$, is also shown for reference (right vertical axis, 'diamond' markers). The images obtained with c=1.2/m (Figure 2) show high positive contrast between the black and white portions of the target for all three cases. However, for the data shown in Figure 3 corresponding to an increased beam attenuation of c=2.1/m, the effects of constructive and destructive interference are observed. The 'Constructive' image shows improved contrast relative to the 'CW' images. The 'Destructive' image shows a dark ring around the white object and a corresponding 'dip' in the energy distribution at the transition between the white object and the black background where η=1. This 'outline emphasizing' feature disappears when the beam attenuation coefficient increases to c=2.5/m (Figure 4). In this case, η>1 for all **r**, which results in $k_{destr.}$<0. For both model and experiment, the contrast of the 'Constructive' image is enhanced relative to the 'CW' image.

CW   Constructive   Destructive

f = 62 MHz   *f* = 33 MHz

(a)   (b)   (c)

— model   — experiment

Figure 2.Model and experimental data for c=1.2/m.

CW   Constructive   Destructive

f = 62 MHz   *f* = 33 MHz

(a)   (b)   (c)

— model   — experiment

Figure 3. Model and experimental data for c=2.1/m.
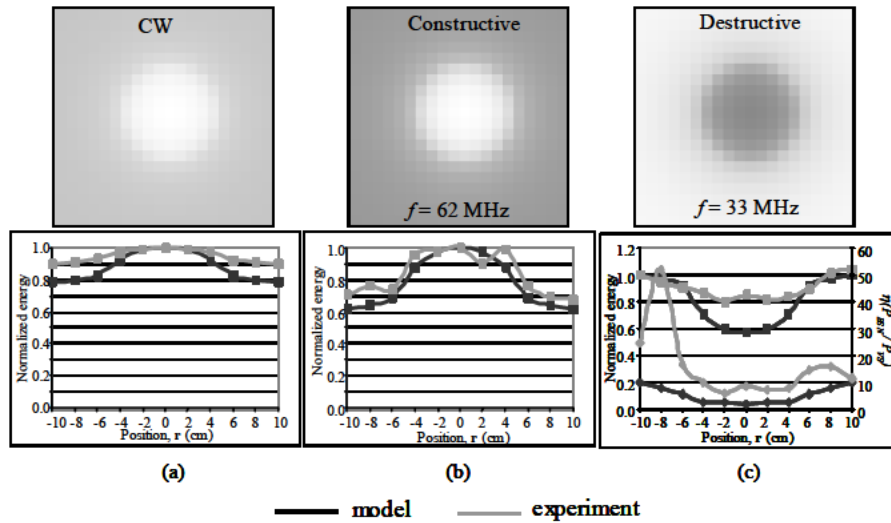
Figure 4. Model and experimental data for c=2.5/m.

In summary, the model and experimental results shown in Figures 1-4 validate the theoretical predictions of the effect of constructive and destructive interference on the target contrast and on the images obtained with a modulated laser imaging system. The good correlation between the model and experimental data give confidence that the MVS program can be used to study the effect of other system and environmental characteristics on the system performance.

IMPACT/APPLICATIONS

Modulated laser imaging systems have the potential to improve the contrast and resolution of underwater images. The Modulated Vision System program developed in this project can be used to predict the performance of these systems and to determine under what conditions the use of this approach will enhance underwater images. The theoretical techniques that form the backbone of this program can also be used to study the application of the modulated technique to other scatter-limited imaging systems, such as those used to image through clouds, fog, and smoke and biological tissue.

TRANSITIONS

The Deputy Director for Force Protection at the Naval Operations Other Than War Technology Center (NOOTW-TC) located at the Naval Surface Warfare Center, Dahlgren Division (NSWCDD) in Dahlgren, Virginia, is interested in the modulated laser imaging system to support Afloat Anti-Terrorism Force Protection (AT/FP) Technology. The proposed use of the modulated laser imaging system is in identifying swimmers in turbid water for Naval ships at the pier or at anchorage. Mr. Elmer Roman has requested cost/scheduling information to support the building of the AT/FP Technology Roadmap and to provide recommendations for future S&T and acquisition activities in this area. The proposed modulated laser system will use the single modulation frequency prototype created under this ONR program as a base upon which a new prototype will be developed to accomplish the specific mission of identifying swimmers in coastal, turbid water.

RELATED PROJECTS

Collaborative work has been initiated with Professor Swapan Guyen from the City College of the City University of New York through a new ONR sponsored Historically Black Colleges and Universities and Minority Institutes (HBCU/MI) program called Research & Engineering Program (REP). NAVAIR is the Navy Laboratory associated with this project, and Dr. Linda Mullen is the Navy Technical Point of Contact. The project, entitled "Time-Resolved Optical Polarization Imaging for Underwater Target Detection", will sponsor undergraduate and graduate students from City College to conduct research regarding the use of short laser pulses and polarization sensitive receivers to improve underwater imaging. This work will complement the modulation work ongoing at NAVAIR.

Collaborative work has also occurred with the Electrical Engineering Graduate Department at Penn State University under the advisement of Professor. Tim Kane. Professor Kane's student, Mr. Daniel Kao, has developed a modulated pulse laser transmitter and is currently conducting experiments in scattering solutions. Mr. Kao will analyze the data to determine how modulation frequencies >1GHz can reduce the detrimental affects of forward scattering on underwater images. Ms. Alicia Messmer, another Penn State graduate student, is developing a bench-top volume scattering function instrument to study the scattering properties and of various scattering solutions, including Maalox and phytoplankton.

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[2] L. Mullen, B. Concannon, A. Laux, E. Zege, I. Katsev, A. Prikhach, "Modulated Vision System," *Proceedings of the 2nd International Conference on Current Problems in the Optics of Natural Waters*, St. Petersburg, Russia, September, 2003.

PUBLICATIONS

L. Mullen, B. Concannon, A. Laux, E. Zege, I. Katsev, A. Prikhach, "Modulated Laser Imaging System," submitted to *Applied Optics,* September, 2003.