FAU Institutional Repository

Tusting, R. (1995). Underwater applications of solid-state laser technology. In *Underwater Intervention '95: man and machine underwater; 16-18 January 1995, Westin Galleria Hotel, Houston, Texas.* (pp. 185-192). United States: Underwater Intervention '95 Conference committee.

UNDERWATER APPLICATIONS OF SOLID-STATE LASER TECHNOLOGY

Robert F. Tusting

Harbor Branch Oceanographic Institution, Inc.
5600 U.S. 1 North
Ft. Pierce, Florida 34946, USA

ABSTRACT

Lasers have found widespread applications in underwater vision, measurement and communications systems due to recent progress in laser technology. The size, weight and cost of visible laser sources have been greatly reduced while their performance, efficiency and reliability have been improved, thereby making many proposed subsea systems not only feasible but practical.

The advances made by solid-state lasers are comparable in many ways to those made by transistors forty years ago. Of major practical interest are the advances made in high-efficiency, red-orange diode lasers which are relatively inexpensive, and compact green, diode-pumped, frequency-doubled lasers. Examples of some of the systems that have recently been demonstrated will be presented along with an overview of some of the solid-state, laser-based systems presently under development.

INTRODUCTION

When lasers were being developed in the 1960s, researchers at US Navy and other laboratories envisioned that they would revolutionize the uses of light underwater. An early proposed application was for LIDAR (Light Direction and Ranging) systems analogous to microwave radar systems employed above the ocean surface since the 1940s. The success of the early LIDAR systems was limited by the availability of reliable and compact lasers. Since then, major improvements have been made and lasers have been successfully used for LIDAR and other underwater optical systems. Some of these applications will be described in a later part of this paper. These include optical imaging, laser-based measurement systems, and two- and three-dimension surface profiling. A major advantage of laser illumination is that it can result in vision systems having a useful operating range several times greater than that of the human eye or video.

Advances in lasers over the past few years have allowed many good ideas to be transformed into practical and effective undersea systems. Two notable developments are small, high-efficiency red-orange diode lasers which are replacing much larger helium-neon plasma tube devices, and diode-pumped, frequency-doubled solid-state lasers which emit in the green at a wavelength nearly optimized for transmission through water.

It is interesting to note that the first laser to be demonstrated used a solid-state material, ruby, as the lasing medium. [1] However, the optical pump energy was provided by a xenon gas-discharge flash lamp. About the same time, plasma lasers were being developed which used a wide range of gases to provide the lasing action. Helium-neon (He-Ne) dominated the low-cost, low power market until recently with its ubiquitous 632.9-nm red-orange emission. [2] Several other wavelengths, including green, are available from He-Ne, but the efficiency and available power are extremely low for these lasers. Argon-Ion gas lasers have been extensively used in underwater systems because they can produce both high power (several watts) and desirable blue-green emission (488 and 514 nm).

MODERN SEMICONDUCTOR LASERS

For several years small, inexpensive gallium arsenide phosphide (GaAsP) laser diodes have been available which produce visible light with wavelengths as short as 670 nm. These are but one type of the wide range of semiconductor devices fabricated from group three—five compounds. Recent solid-state advances have produced high-efficiency laser diodes with a slightly different composition (AlGaInP), which emits at a wavelength of 635 nm. The difference between 670 and 635 nm may seem trivial. However, the human eye is seven times more sensitive to light having the shorter 635-nm wavelength than to 670-nm emission. When passing through water, the shorter wavelength radiation is also attenuated less; over a distance of 10 meters, a 670-nm light source would have to be three times as intense as a 635-nm source to provide the same illumination. As technology progresses, shorter wavelength diode lasers will surely become available.

Solid-state diode lasers are rapidly replacing He-Ne, gas-discharge lasers which have been the mainstay of low-power, inexpensive underwater laser measurement systems. [3, 4] The reasons are:

- Size
- Efficiency
- Simplicity

Figure 1 is a photograph of a 635-nm diode laser which produces approximately 10 mW of beam power. The laser is packaged in an underwater housing designed for operation to 6,000 meters and weighs approximately 1/2 pound in water. The electrical power required is less than 1 watt. A comparable underwater laser which uses He-Ne plasma tube technology is nearly 20 times as large, 10 times as heavy (in water) and requires 30 times as much electrical power (refer to Figure 2).

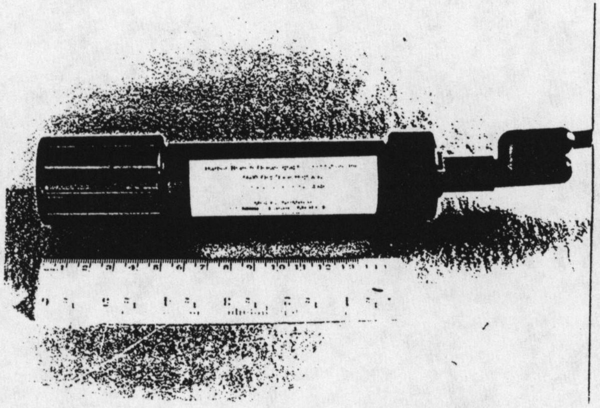

Figure 1. Photograph of a 10-mW, 635-nm diode laser packaged for operation to 6,000 m.

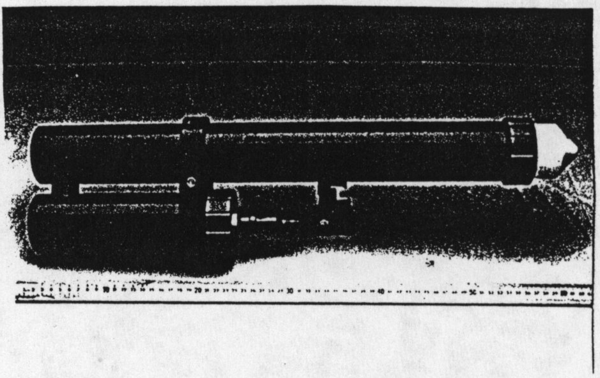

Figure 2. Photograph of a 7-mW, 633 nm He-Ne laser packaged for operation to 6,000 m.

Because of its relatively large size, a He-Ne laser produces a low divergence beam that can often be used without additional optics. A diode laser, on the other hand, produces a widely divergent beam (typically 10° by 40°) so that a collimating lens is essential if a narrow beam is desired. Figure 3 is a photograph of a diode laser module that we have been using. The size is 2-inches long by 1/2-inch diameter, and even smaller units are commercially available from this and other manufacturers.

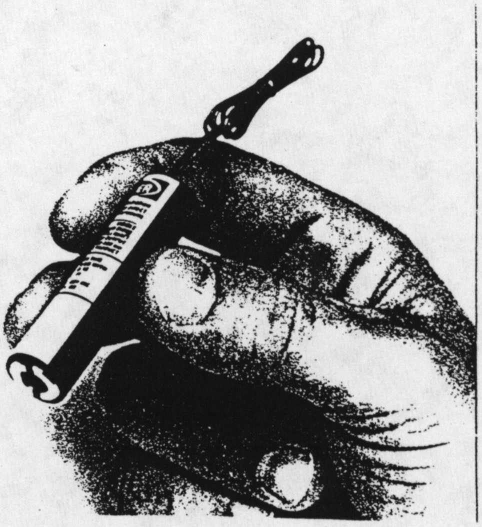

Figure 3. Diode laser module used in micro-laser of Figure 1.

Included in the module are the laser diode, a current-regulating power supply, and collimating/focusing optics. This particular module is convenient in that the user can easily change the range at which a minimum spot size is obtained, plus the position of the laser diode can be physically adjusted within the module to align the beam along the axis of the cylindrical housing.

Basic geometrical differences between He-Ne lasers and diode lasers produce significant dissimilarities between their output beams as illustrated in Figure 4. The typical angular resolution of the human eye is included for comparison. The He-Ne beam is small as it exits the laser, but in the absence of a collimating lens, expands typically 1 mm for each meter traveled (1 milliradian divergence). The diode laser beam is larger (typically 5 mm) as it exits the laser module and can be either collimated or focused to obtain a minimum spot size at a range of several centimeters to many meters. The beam shape is not circular unless more complex optics are provided. Beam size as a function of range is illustrated in Figure 4 for a focus distance of 2 meters and 4 meters. Because of its small size, and the beam-shaping optics, a diode laser requires careful mounting and precise adjustments to obtain good beam alignment.

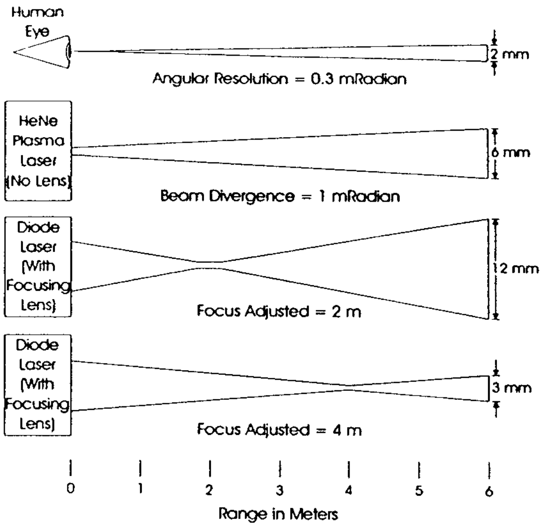

Figure 4. Output beam patterns from He-Ne and focused diode laser.

DIODE-PUMPED, FREQUENCY-DOUBLED LASERS

The virtues of blue-green light for in-water applications are well documented. [5, 6, 32] An exciting development of the late 1980s was the demonstration of compact, solid-state lasers which produced green radiation by second harmonic generation and other nonlinear mixing techniques. [7, 8, 9] Nonlinear optical effects had been around for many years but this was the beginning of their application to practical laser systems.

Various schemes of laser frequency conversion have been developed, but one of those most commonly used commercially involves using a high-efficiency, high-power diode laser to optically pump a crystal of neodymium doped yttrium aluminum garnet (N:YAG) which lases at 1064 nm. [7] The resulting output radiation is then converted to 532-nm laser light by passing it through a second frequency-doubling crystal.

The number of manufacturers offering all solid-state green lasers is growing rapidly. Size and cost are steadily decreasing as output power and efficiency increase. In 1987, the most powerful diode-pumped green laser available was 5 mW. By 1989, 80-mW units were being sold; and by mid-1994, 400-mW, 532-nm laser systems were advertised with a laser head measuring only 4 by 4 by 13 inches. The required power supply is several times larger. However, this system is significantly more compact and efficient than an argon-ion gas laser which might have been considered for the same underwater task a short time ago.

For those of us who are interested in low-power green lasers for underwater measurements and quantitative photography, there have been dramatic advances in size and cost reduction. One manufacturer offers up to 5 mW from a laser head slightly larger than 1 x 1 x 4 inches. Another advertises up to 100 mW of 532 nm from a laser head 1 1/4 x 1 3/4 x 2 1/2 inches. Both designs incorporate thermo-electric temperature control within the laser head package. Again, the required power supplies are several times larger than the laser head, but they can be mounted remotely and connected by a multiconductor cable. These small green lasers show great promise for some of the laser-based imaging and measurement systems being developed. The higher power units have been used in a wide range of applications for several years. Some of these systems will be briefly described in the following sections.

SIMPLE APPLICATIONS

One of the more basic applications of a laser underwater is as a visual pointer. Low-power lasers are used to indicate where a camera is pointing, to aim a tagging gun, and to locate the position of objects on the seafloor.[1] [4] One such application is shown in Figure 5.

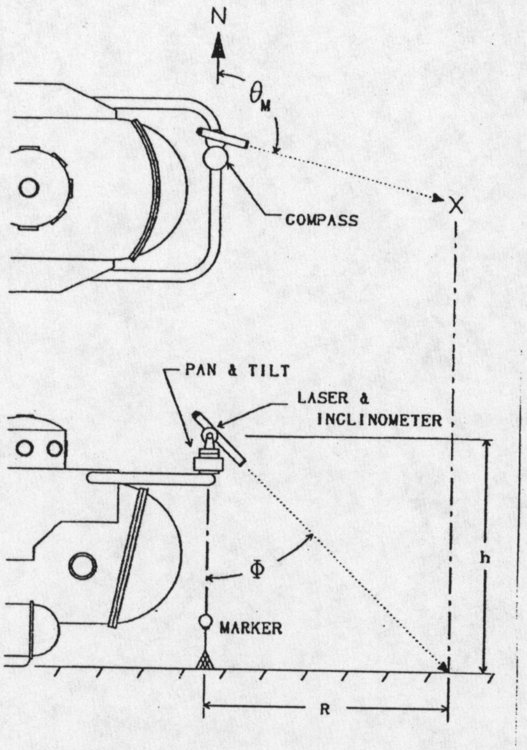

Figure 5. A proposed method of optically measuring the position of objects on the seafloor.

The laser is mounted on a pan-and-tilt mechanism as high as practical on the submersible to obtain a long measurement baseline and improved accuracy. The horizontal (pan) angle of the object is measured with respect to north by an electronic compass. The vertical (tilt) angle is indicated by an electronic inclinometer. The height h above the bottom is known, and the two angles θ_M and Φ are recorded after the laser has been pointed at the object of interest. The position of the object with respect to the reference marker is then calculated using simple geometry. The positions of other points or objects can subsequently be measured. Quantities such as the distance between two or more objects can then be calculated. Although the system shown in Figure 5 has yet to be used underwater, it is employed as a rapid terrestrial survey and measurement tool where high-precision is not required.[2]

A pair of parallel mounted lasers has been widely used with underwater viewing and camera systems to provide size information directly on the recorded image. [10-14] Other configurations allow range information and orientation to be directly derived. Increasing the number of lasers mounted adjacent to a camera and projecting into the field-of-view provides sufficient information for performing a quantitative analysis of the images. [13, 15, 16, 17] The four-laser configuration of Figure 6 has been recently implemented. With proper calibration of the camera/laser system, the determination of range and tilt angles between the camera and object plane can be calculated for a general case where the focal length of the camera lens is unknown.

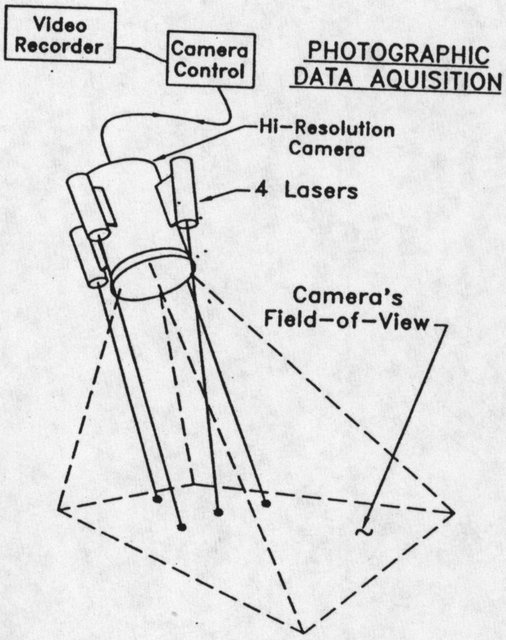

Figure 6. Quantitative photographic method using four laser pointers.

Fiber-optic-coupled illuminators have been demonstrated which allow the laser to be

---

[1] U.S. Patent No. 5,046, 259, 1991

[2] CRITERION™, Laser Technology, Inc.

located remotely from the projected illumination. At the Monterey Bay Aquarium Research Institute (MBARI), green He-Ne lasers have been used with fiber-optic cables and graded-index lenses to obtain very small laser light sources which are mounted unintrusively on their underwater camera. [18]

The recent advances of small 635-nm diode lasers and diode-pumped, frequency doubled 532-nm lasers, summarized earlier in this paper, allow them to be conveniently mounted on undersea camera systems. The power efficiencies of the red-orange diode lasers have improved one-hundred fold over He-Ne devices so that their use with diver-deployed cameras is practical. The availability of small and relatively economical green lasers will allow the simple quantitative photographic methods briefly described above to be used at ranges which match the upper limits of conventional video and still photography. For longer range imaging, advanced laser methods are needed.

LASER-BASED IMAGING SYSTEMS

One of the dreams of underwater photographers has been to obtain images at ranges in excess of those possible with conventional cameras, low-light-level cameras, and the human eye. Practical laser-based imaging and ranging systems developed in the late 1980s have made this possible. [19-22] Basically two approaches were pursued—range gating and laser scanning. Several methods of laser scanning will be superficially described below. For a more complete discussion, several readable references are provided.

LIDAR & LASER RANGE-GATED VIEWING

An old idea that has recently become feasible because of suitable hardware is the pulsed-laser illuminator/range-gated optical receiver viewing and ranging system. [19, 23] If an image is not required (for example a simple LIDAR), a single pixel receiver such as a phototube can be used. However, for more detailed information about an object, an image tube which can be time gated must be used. With this method, a short blue or green pulse of light (a few nanoseconds) illuminates the area of interest and a high-gain imaging device looks at the same region for a short time. The receiver is gated on for a few nanoseconds at a selectable time after the transmitted light pulse. If the time delay matches the transit time of the light pulse from the laser to a target and back to the receiver, an image of the target will be obtained. If not, there will only be the backscatter from the small volume of water illuminated. In a simple mode of operation, the delay time is incrementally varied for each pulse until a target is obtained. Once detected, a moving target can be automatically tracked by gating the receiver either sooner or later (nearer or farther). A basic range-gated imaging system needs a nearly stationary platform. With the small size and high efficiencies available from Nd:YAG lasers, diver-operated systems are feasible. [23]

LASER SCANNING SYSTEMS

Several approaches to laser scanned imaging have been proposed and demonstrated. The simplest system uses a scanning laser (i.e., raster scan) to illuminate the scene and a single pixel receiver (i.e., photomultiplier tube) to view the entire scene. Such a system has been shown to produce better images in clear water than more conventional video cameras, although the wide field-of-view of the receiver made it vulnerable to scattered light from the laser. [20] A logical improvement to this method is to synchronously scan a receiver having a greatly reduced angular field of view so that it views only the small area illuminated by the laser. [21] Both of these approaches require that the platform on which the imaging system is mounted must be stable for the time duration required to obtain a complete frame.

A recently developed and highly successful variation of the synchronously scanned receiver approach involves scanning the laser in one dimension only. The scanning in the second dimension is provided by the constant forward velocity of the imaging system. [24, 25, 26] This approach, called the LLSS (Laser Line Scan System), has been successfully demonstrated many times over the past few years. [33] The LLSS produces a long-range optical image of the ocean bottom as it travels in a straight line (at an ideally constant velocity) while sweeping the laser beam from left to right. The highly directional optical receiver is synchronously aimed in the direction of the illuminating laser beam. Candidate vehicles include submarines, tow-bodies, ROVs, and AUVs. The early models used argon-ion lasers which were large and power hungry. Recent designs are using solid-state, diode-pumped lasers for obvious reasons. At least two companies are actively engaged in improving and marketing smaller and more rugged designs, and these systems will have a major impact on future optical search and survey activities. A number of research laboratories and ocean service organizations are acquiring LLSSs.

SPOTSCAN 2-D SYSTEM

Another innovative approach to laser-based optical detection and ranging is the SPOTSCAN 2-D System developed in the late 1980s. [27] With this method, a laser generated line (or stripe) is projected into a video camera's field of view. The image of the scanned stripe is recorded and range information derived from triangulation. Several systems are in use for survey and research applications. Kuster has performed a theoretical analysis and evaluation of the system under controlled conditions and conducted field tests to determine its practical capabilities and expected accuracy. [28]

3-D IMAGING

Three-dimensional underwater imaging is another goal that has been pursued for many years. Conventional stereo methods provide the viewer with a sense of telepresence but have had limited applications for three-dimensional measurements. [29]

A novel approach was developed at Harbor Branch Oceanographic Institution, Inc. (HBOI) in the early 1990s. [16, 30] This method uses a two-dimensional scanned laser beam to illuminate the scene. The scan pattern is similar to that used in the laser scanners described earlier. The optical detector is located at an accurately controlled offset position so that triangulation can be used to measure range. The optical detector is a lens and a position-sensitive detector (PSD) which produces output signals which represent the position of a light spot on the diode.

The direction of the illuminating laser beam is measured at all times. This information along with the x-y coordinates of the light spot reflected from the scene, as measured by the PSD, allows the three-dimensional position of the illuminated surface to be calculated in nearly real-time. [31] A 160-mW, diode-pumped, frequency-doubled N:YAG laser was used in the prototype system. Further development of these techniques are underway at HBOI to improve the performance in turbid water and to reduce the size of the system.

COMMUNICATIONS

Lasers have been used to communicate between high-flying aircraft and deep-running submarines. [32] High-data-rate communications between submerged vehicles running on parallel courses in the deep ocean have also been demonstrated using a diode-pumped, frequency-doubled green laser.

CONCLUSIONS

A wide spectrum of underwater imaging and measurement systems based on the unique properties of lasers has been developed over the past few years. More applications, limited only by the imagination and creativity of those working in this field, are sure to be developed. As the size and costs continue to decline, the number of practical uses for lasers in the undersea environment will continue to expand.

ACKNOWLEDGMENTS

The author would like to acknowledge the work of many engineers and scientists who have pioneered the development of the systems briefly described in this paper. My thanks to Annell Nelson for her care in preparing the manuscript. This paper is HBOI Contribution No. 1056.

REFERENCES

1. Maiman, T.H., Stimulated Optical Radiation in Ruby. Nature, V.187, pp. 493-4, August 1960.

2. Javan, A., W.B. Bennett, Jr. and D.R. Herriott, Population Inversion and Continuous Optical Maser Oscillations in a Gas Discharge Containing a He Ne mixture. Physical Review Letters, V.6, pp. 106-110, February 1961.

3. Caimi, F.M. and R.F. Tusting, Application of Lasers to Ocean Research and Image Recording Systems. Proceedings of the International Conference on Lasers-87, pp. 518-524, 1987.

4. Tusting, R.F., Enhancement of Undersea Measurement and Vision Systems Using Lasers. Proceedings of ROV-90, pp. 284-290, 1990.

5. Jerlov, N.G., Marine Optics, Elsevier Oceanography Series, NY, 1976.

6. Allwood, R., Lasers: Their Application in Water. Underwater System Design, pp. 26-28, January - February 1985.

7. Byer, R., Diode Laser-Pumped Solid State Laser. Science, V. 239, pp. 742-747, 1988.

8. Byer, R.L., Nonlinear Frequency Conversion Enhances Diode-Pumped Lasers. Laser Focus World, March 1989, pp. 77-86, 1989.

9. Lin, J.T., Progress Report: Diode Pumping and Frequency Conversion. Lasers & Optronics, July, 1989, pp. 61-66, 1989.

10. Tusting, R.F., Nonconventional Techniques for Sampling and Collecting Marine Organisms. Proceedings of PACON-86, pp. MRM 1-18, MTS, 1986.

11. Tusting, R.F., and F.M. Caimi, Biological-Research Applications of Undersea Laser Systems. Proceedings of PACON 88, pp. OST 1/19-20, MTS, 1988.

12. Auster, P.J., L.L. Stewart and H. Sprunk. Scientific Imaging with ROVs: Tools and Techniques. Marine Technology Society Journal, V.23, No. 3, pp. 16-20, 1989.

13. Tusting, R.F. and D.L. Davis, Laser Systems and Structured Illumination for Quantitative Undersea Imaging. Marine Technology Society Journal, V.26, No. 4, pp. 5-12, 1992.

14. Goddio, F., The Tale of the San Diego. National Geographic, July, 1994, pp. 35-57, 1994.

15. Davis, D.L. and R.F. Tusting, Quantitative Benthic Photography Using Laser Calibrations. Proceedings of Under Sea World-91, pp. 39-43, West Star Productions, 1991.

16. Caimi, F.M., et al., Advanced Underwater Laser Systems for Ranging, Size Estimation, and Profiling. Marine Technology Society Journal, V.27, No. 1, pp. 31-41, 1993.

17. Tusting, R.F., and D.L. Davis, Improved Methods for Visual and Photographic Benthic Surveys. Proceedings of Diving for Science-93, pp. 157-172, AAUS, 1993.

18. Davis, D. and S. Echemendy, Personal Communications, 1992.

19. Gilligan, L.H., Range Gated Underwater Viewing. SPIE V.980 Underwater Imaging, pp. 36-40, 1988.

20. Coles, B.W., Recent Developments in Underwater Laser Scanning Systems. SPIE V.980 Underwater Imaging, pp. 42-52, 1988.

21. Kulp, T.J., et al., Current Status of the NAVSEA Synchronous Scanning Laser Imaging System. SPIE V.980 Underwater Imaging, pp. 57-65, 1988.

22. Cummings, J.D. and R.F. Cybulski, Underwater Optical Imaging with Laser Sources. Proceedings of Undersea Defense-89, pp. 77-82, 1989.

23. Swartz, B.A., Diver and ROV Deployable Laser Range Gate Underwater Imaging Systems. Proceedings of ROV-93, pp. 193-198, 1993.

24. Palowitch, A., Exploring the Limits of Optical Underwater Imaging Systems. Proceedings of MTS-91, pp. 813-819, 1991.

25. Leatham, J. and B.W. Coles, Use of Laser Sensors for Search and Survey. Proceedings of Intervention-93, pp. 171-186, 1993.

26. Gordon, A., Underwater Laser Line Scan Technology. Proceedings of Intervention-93, pp. 164-170, 1993.

27. Klepsvik, J.O. and H.O. Torsen, Recent Advances in Accurate Underwater Mapping and Inspection Techniques. Proceedings of the International Ocean Technology Congress, Honolulu, January 1989.

28. Kusters, J.G., Analysis and Application of an Underwater Optical Ranging System. MS Thesis MIT/WHOI, September, 1992.

29. Hamner, W. et al., Three-Dimensional Video as an Underwater Tool. SPIE V.980 Underwater Imaging, pp. 2-9, 1988.

30. Caimi, F.M., D.C. Smith and D.M. Kocak, Undersea 3-D Imaging and Mapping for Inspection and Research, Advanced Imaging, July 1992, pp. 32-36, 1992.

31. Massey, J., Underwater Laser Mapping for Ship Husbandry. Proceedings of Underwater Intervention-94, pp. 312-318, 1994.

32. Marshall, L.R., Blue-Green Lasers Plumb the Mysteries of the Deep. Laser Focus World, April 1993, pp. 185-196, 1993.

33. Hellemn, J.E., T.J. Fredette and D.A. Carey, Underwater Environmental Survey Operations Using Laser Line Scan Technology. Proceedings of Underwater Intervention, pp. 319-327, 1994.