UNDERWATER LASER APPLICATIONS

M.R.WALL

Atomic Weapons Research Establishment, Aldermaston, Berks

Several methods are discussed for utilizing the properties of lasers to improve visibility where scattering limits range. Simple pulsed viewing systems are being evaluated in underwater applications. Scanning systems offer alternative advantages which would be preferable in some circumstances. Where it is essential to have real-time presentation of data with a large video bandwidth, lasers could be used for transmissions up to 0.75km. Laser navigational aids in the favourable visibility of deep ocean could give ranges up to 1km. There are also a variety of surveying possibilities. Particle velocity, turbulence, current and similar measurements are being made in laboratories using Doppler techniques. These techniques will shortly be extended to measurements in the sea. Holography could permit plankton counting, species identification, speed, distribution and behavioural studies without sample interference and whilst the study vessel is in motion.

THE OPTICAL WINDOW in water is restricted to the blue-green and green parts of the spectrum; there are no narrow wavelength regions in which it is possible to obtain lower attenuation (Fig. 1a). Both the argon and krypton gas lasers produce appreciable c.w. power in the blue or blue-green regions. The argon laser has produced as much as 1OW though it is inefficient. Pulsed gas lasers are also available and include argon, krypton and neon. Pulsed solid-state lasers suitable for underwater application involve the use of neodymium doping in various host materials, the most simple and well-developed of these being neodymium in glass. In this case, emission is in the infra-red region and frequency-doubling techniques are necessary to produce light in the green part of the spectrum. Peak powers of several megawatts have been obtained.

UNDERWATER LIGHT SCATTERING

Underwater viewing is made difficult, not so much by attenuation, but by scatter which dilutes the contrast with which the object can be seen. This is so whether the target is lit by sunlight from above, or by a light source underwater. The problem is worse if the light source is near the viewer because light scattered from suspended matter in the water is unattenuated, while that reflected from the target has been attenuated.

The eye can distinguish changes in light intensity of about 2%. Thus a black and white target cannot be distinguished when the scattered light is more than fifty times the light received from the white parts of the target. The distance at which the target becomes indistinguishable is called the visibility-length. This varies from about 70m in the ocean down to zero in tidal estuaries (average values are 5 to 10m). Under good conditions about half the light is lost by scattering and the other half by absorption. In more difficult conditions the scattering loss will

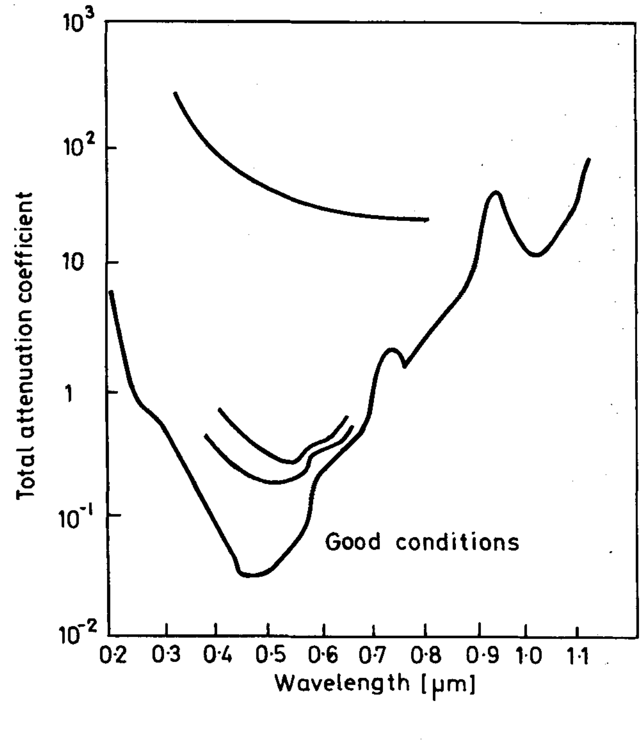


Fig. 1a. Optical window in water

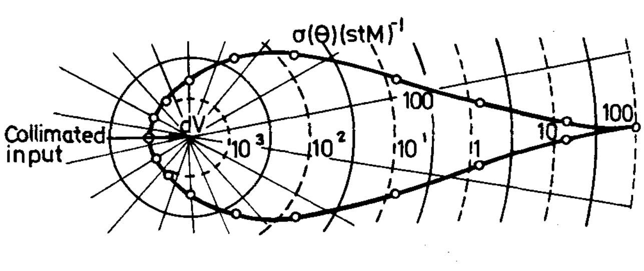


Fig. 1b. Typical scattering function

greatly exceed the amount lost by absorption. Most of the scattering particles will absorb some of the incident light so the remaining light is also reduced by subsequent scattering. It appears, however, that over long distances more scattered light may illuminate the target than direct light.

Details of the scattering process, time delays involved and scattering functions are all poorly understood and satisfactory measurements are lacking. In addition, the available mathematical techniques are inadequate for calculating the light back-scattered over long distances even if the measurements were available.

The attenuation-length is the distance in which the light would be attenuated by both scatter and absorption to 1/e of its original value, that is about 33%. It follows that for good conditions the visibility is about four attenuation-lengths.

Measurements as a function of angle show that relatively little light is scattered backwards (Fig. 1b). To reduce this back-scatter the light should be as close to the target as possible and a directional light source should be used from one side of the object rather than directly in front. Assuming that all the scattered light is rejected both on the outward and return path, the limitation on viewing is when the signal level deteriorates to the point where only a few photons are returned from the target for each picture point. Assuming that over 10 000 picture points are required (not a high resolution) and 1J of light is transmitted, then the range is about three visibility-lengths. This is not very dependent on radiated power or resolution requirements. Various workers have given similar theoretical results varying from 10-13 attenuation-lengths.

Recently some workers have suggested that, by making use of the forward-scattered light in lower-resolution systems, this range might be improved. However, if much of the scattered light is accepted by the receiver, the intrinsic noise due to photon fluctuations will mask all signals.

DISCRIMINATION AGAINST SCATTER

Pulsed range gating

If a very-short pulse of light is transmitted there is a continuous return of this light to the receiver by scatterers at steadily increasing range. Light returned from the target is delayed by the transit time from transmitter to target and back to the receiver. If the receiver is not opened until the light from the target returns and is closed when the light from this ceases, most of the scattered light is avoided (Fig. 2a).

Short light pulses and short receiving times give better discrimination and higher contrast. A receiver pulse which is shorter than the light pulse wastes light returned from the target without significantly improving discrimination (Fig. 2b). Conversely, a receiver pulse longer than the light pulse gives a small depth over which an object will be seen with similar brightness but decreases the effective depth discrimination.

There have been many demonstrations of the technique, and depth-proof apparatus has been produced, Fig. 3, but the major difficulty is caused by very large changes in signal returns as a function of range. At extreme range signals will be 10^{-6} of those just in front of the camera. If the range gate is 1/6 of the

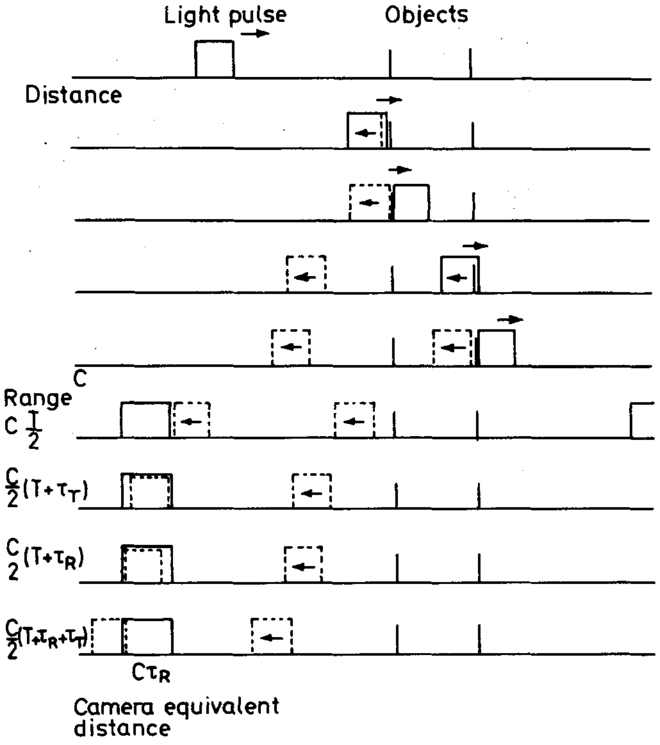


Fig. 2a. Pulsed range gating

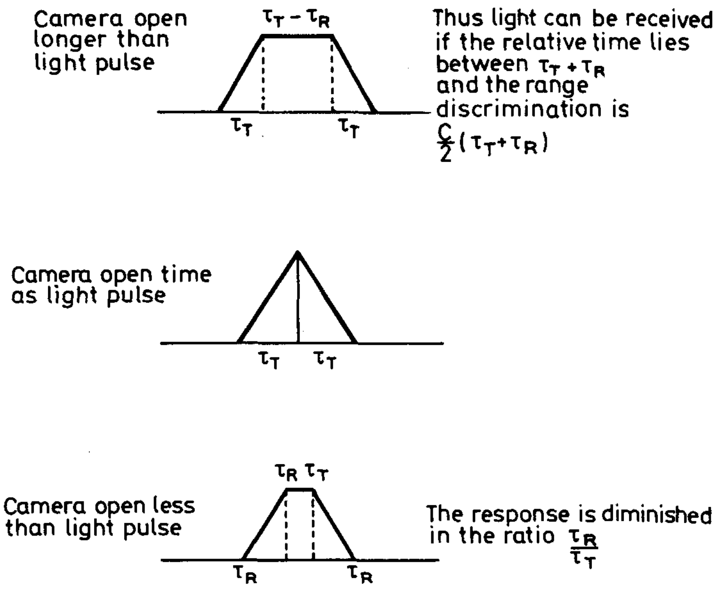


Fig. 2b. Receiver discrimination

total range (half a visibility-length) the signal level for the nearest is ten times that of the farthest possible target. In addition, variations due to the triangular or trapezoidal form of the range-gate efficiency could lead to a further factor of three or four.

Thus it is essential that any receiving camera has not only a system range over six orders of magnitude, but within a particular range-gate, the dynamic range of the system needs to be at least 40 before taking into account variation of the reflectivity of the target. Thus a workable system has been dependent upon the development of an electronic 'gateable' camera tube with this kind of dynamic and system range, and preferably with television readout. The recent development of a satisfactory tube (Isocon) has given fresh impetus to research into this technique at AWRE.

The Isocon is very sensitive (about 10 × photon noise limit) and has been operated with an image intensifier. It has a dynamic range of 600 which with a.g.c. can be raised to 10 000 without serious blooming and overload.

Because the tube is like an image orthicon, it should be possible to gate it in times as short as 4ns (corresponding to 1.8m range depth).

Laser scanning television

If a collimated laser beam is scanned across the target point by point then all the scattered light returned to a photomultiplier receiver can be used to produce a television image synchronized to the transmitter raster.

To prevent the scattered light saturating the system the scanning beam should be offset from the detector as much as possible. However, this is not adequate unless the receiver reception cone and the maximum operating range are rather limited.

Geometrical filtering

By combining the laser television with a scanning receiver the reception cone can be reduced (Fig. 4). Image-dissector tubes provide this capability but mechanical systems are also possible. Effectively a small hole scans the image in synchronism with the laser illumination. Only light which is scattered more than once can enter the field of view of the receiver.

In this way the scattered background may be reduced and, hence, at short ranges and moderate resolution even small separations can give small range depths. This may itself be a problem. Great flexibility in method of use and display is also possible. It is probable that the scattering discrimination will be much better than with pulsed gating. Light used to illuminate early parts of the picture has a very long time in which to diffuse out of the region viewed and will be heavily attenuated. The method also eliminates some forward scattering of light from the target.

Synchronous scanning

In air a scanning transmitter and receiver can be operated at high enough speeds for the transit time of the light to be important. The system can then behave as a c.w. range gate. It is feasible to build a system with about 15m discrimination in water but this is not adequate in most circumstances.

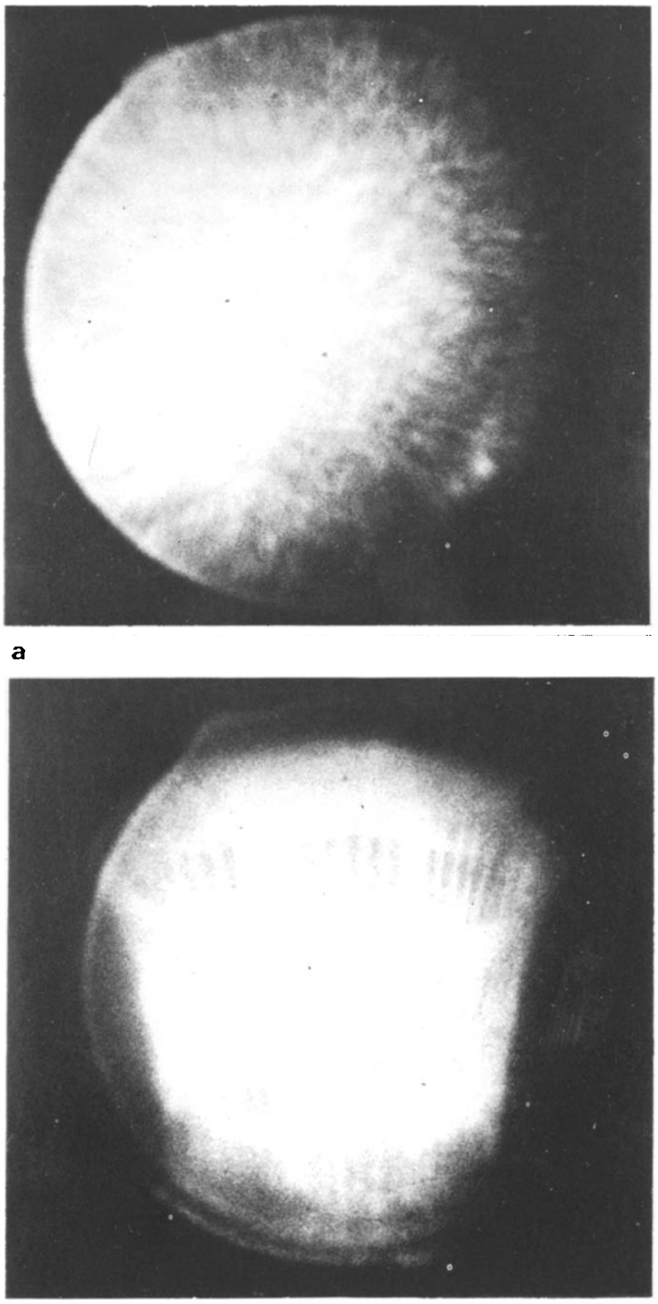
Line scan geometrical filter

If the vessel carrying a geometrical system is travelling at an adequate speed then frame scanning is not needed. It would then resemble the line scan technique of high resolution radar mapping and is suited to 'search' operations.

Flexibility of scanning techniques

Discrimination can be adjusted by altering transmitter-receiver separation, beam divergence and diameter, receiver focus and hole size. Flat targets such as the sea bed can be scanned in one frame by tilting the field of view. Panoramic views up to 360° are possible using vertical scanner separation.

Image dissectors are being developed for systems of this kind, but mechanical systems are somewhat



a

b

Fig. 3. Contrast improvement with range

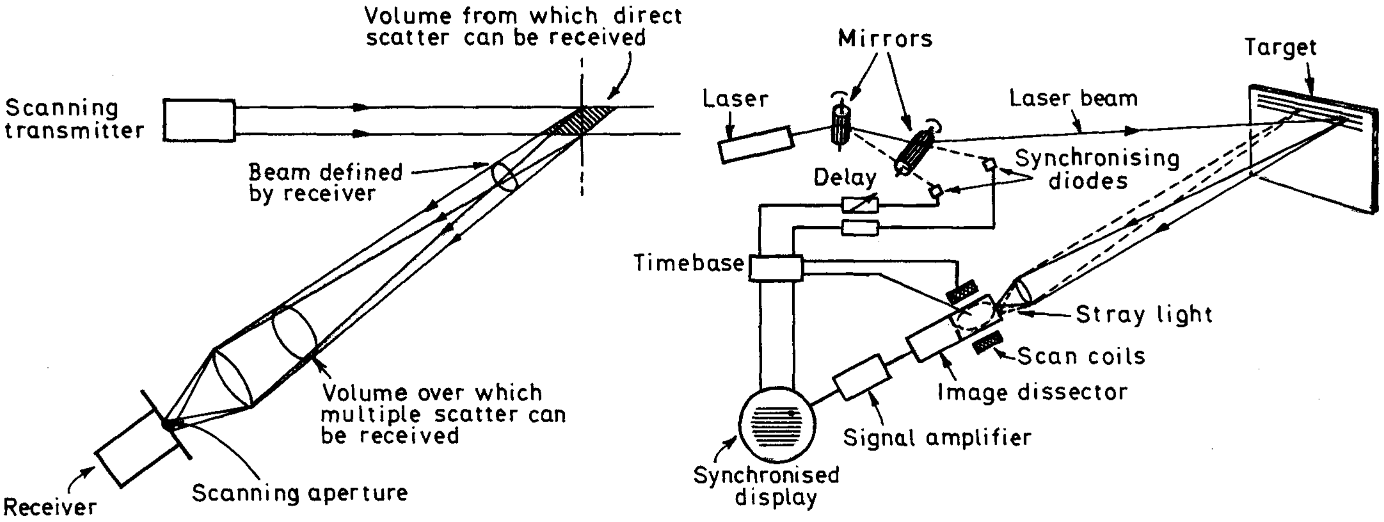


Fig. 4. Geometrical filtering

easier to build because of the difficulties of alignment and the electron beam and deflection distortion found in image dissectors.

By applying known techniques to overcome these problems, image dissectors become inherently more flexible. The remaining difficulties are caused by the need for a.g.c., and sophistication of display systems to utilize information from different ranges.

It has recently been suggested that, where scattering exceeds the direct attenuation by an appreciable amount, scatter arriving at a target exceeds the monopath radiation beyond a few attenuation lengths. Thus, using a scanning discrimination system may exclude useful light from illuminating the target. A trade-off is possible in the resolution capabilities at large ranges.

Circular polarization

For a target illuminated with circularly polarized light the component returned from the target is often depolarized, while that from single scattering at particles is of the opposite sense of circular polarization. The receiver uses a circular polarizer to discriminate the single and odd-multiple scatter.

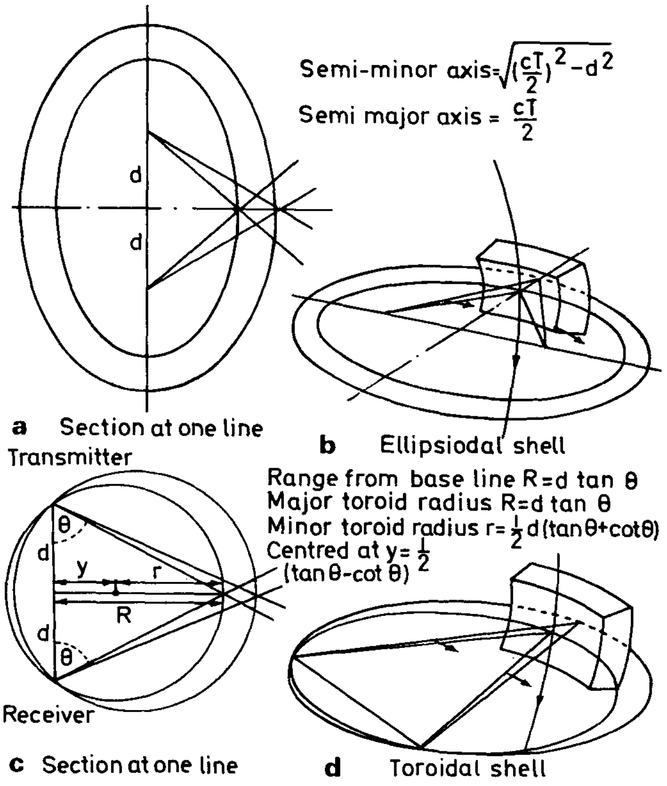
The advantage of a laser in this case rests mainly with the power available at the right wavelength; initial polarization gains a factor of two or three in intensity.

RANGING

Excluding the circular polarization and the laser television system, all the systems described above can give range information.

The pulsed range-gated system could have a precision better than 0.3m while the geometrical filtering could be better than 3cm over practical ranges. The range of the detected volume is a function of the position in the field of view. For the pulsed range-gated system the detected volume lies between two ellipsoids (spheres, if transmitter and receiver are coaxial) see Fig. 5a.

For the geometrical filtering system the volume lies between two toroidal surfaces (the toroid has no central hole!). Fig. 5b. Along the scan line the range can vary rapidly depending on the separation between laser and detector but in the panoramic version it is constant.



Figs 5a & b: Range volume: pulsed gating
c & d: Range volume: geometrical filtering

Laser rangefinders

Pulsed laser rangefinders have been developed for battlefield use and also for cloud tracking. In principle the techniques, which determine the time of return of a pulse superimposed on a smooth exponential return from the scattering medium, are directly applicable. Underwater use requires frequency-doubled Nd YAG lasers and high clock rates to achieve improved range accuracy.

Both pulsed and swept-frequency laser altimeters have been made for airborne use. These are directly analogous with radio and radar devices and could, therefore, use pulse-code modulation, chirp and pseudo-random noise-coding to improve the ranging precision. In the swept-frequency case the coherent return from the sea bed would permit operation in strong scattering conditions without recourse to range-gating or geometrical filtering. Using this kind of technique in low-flying aircraft, depth, in shallow-water conditions, can be measured by subtracting the surface returns from the sea-bed returns.

Optical techniques developed for surveying and geodesy are also likely to be applied. Cooperative targets, mounting a retroreflector, can be measured in range using multiple-frequency modulation at microwave frequencies or single-frequency modulation if changes in range are measured continuously.

Navigation

If two fixed and recognisable reference points are available with known separation, then any ranging system such as those mentioned above can be used for relative navigation by trilateration. If the separation of the points is not known then measurement of the two ranges and the angle between the direction of the two references will suffice. Mounting a laser system in place of a theodilite will therefore allow precise navigational measurements in slow-moving craft. Reference marks would preferably not be natural features of the underwater terrain but retroreflectors. This would improve the range capability because of the high reflectivity and directional return. Systems are being developed for accurate above-water navigation near the coast where radiofix methods are sometimes prone to error.

Navigational coordinate systems are also possible using modifications of the geometrical filtering system. Since the receiver can give the scan line and scan angle at which the target lies, range accuracy is dependent on the base-line length, the transmitter and receiver beam-widths and the scanning uniformity. This would facilitate tracking and homing on mother ships and, in particular, search operations could be better organised.

Laser beams are used to define fixed lines along which vessels can move. These are already applied in dredging operations and might be used both above and below water for defining a line of search. Existing beam-riding detectors, such as quadrant photomultipliers, are suitable. Forward scatter is again the factor limiting the range, probably to about twenty attenuation lengths.

COMMUNICATIONS

Although it has been suggested that forward scatter can increase the range of laser systems used for communications, for oceanology it seems unnecessary to use lasers unless they are already present in another role. Acoustic systems can transmit data over long distances, unless the required data rate is high or secrecy is necessary. It is difficult to imagine a high data rate not involving a viewing device and it would need to be free-roving and remote from the recording centre in order to require a transmission link. However, for communicating video data it should be feasible to obtain something like two and a half times the range of a viewing system or about 25 attenuation lengths.

PARTICLE COUNTING & SIZE ESTIMATION

Lasers can be focused to a diffraction-limited spot. By observing this brightly illuminated volume from the side, individual particles may be counted by the flash of light they produce on passing through. If the particles are small then the direction in which the light is scattered is fairly well defined according to size. Hence, their size classification is possible. Large particles passing through this volume can be given a well-defined velocity so the time for which light is scattered will give some measure of the size. Normal nuclear instrument counting techniques can be applied. The method has been used for counting yeast cells in fluid flows and design studies have been made for a continuous plankton counter.

VELOCITY MEASUREMENT

Laser Doppler systems have been developed capable of measuring velocities over a wide range and with weak signal returns. Thus, it is possible to obtain satisfactory Doppler velocity measurement of suspended particles in water in concentrations as low as one part in two million. Sea water in general has much higher particle concentrations and it is therefore possible to measure local water-flow velocities. The laser Doppler devices do not have to use the line of transmitted light for the return scattered Doppler shifted light and they may be focused, thus isolating very small sample volumes.

The local flow around ships in motion could be measured to give hydrodynamic data on boundary flow. With more remote isolated volumes currents and drift rate could be measured and local flow patterns in waves determined.

These systems exist in engineered forms. Since many applications would be shipborne and not require depth proofing, it is surprising that they do not seem to have been applied.

HOLOGRAPHY

A holographic recording is capable of being replayed in such a way that the original wavefront can be obtained again at any subsequent time and hence it is possible to use this wavefront as if it were in its original position but without the water! It is possible to see objects in three dimensions, to focus on them, to use a microscope to view them (if they have been recorded with sufficient aperture and angle of view), and to process the wavefronts in any way that might give useful information in the original setting.

The advent of pulsed solid-state lasers capable of front-illuminated holographic recording will permit particle velocities up to at least 30m/s. Three-dimensional recordings of plankton can be obtained and from these it would be possible not only to count the plankton individually, but to obtain their volume distribution and identify them. By double pulsing the recording laser it would be possible to obtain drift, settling rate and velocity distribution of mobile plankton.

A difficulty which has been underestimated, is the unusual appearance of coherently illuminated objects, particularly at high magnification.

The techniques of holography are also applicable to the performance analysis of vibrating objects. In particular the Powell and Stetson technique has been used to investigate the uniformity in response of large area sonar transmitting transducers.

OPTICAL INFORMATION PROCESSING

A normal image of an object is not necessarily the most convenient form for subsequent analysis. The diffractometer has been used in a wide variety of ways for reprocessing information into a suitable form for subsequent measurement. The simple use of the diffraction pattern of small particles can give approximate information on particle-size distribution and number. The combination of diffractometers with holographic techniques has led to matched filtering which can recognise a signal amongst a noisy background. Thus, for simple cellular organisms of fixed shape it should be possible to make matched filters which can identify their existence in a sample, and a classifying machine is also feasible. To facilitate this kind of operation a flow of liquid through the apparatus would be necessary so that the cells would always be presented in a preferred orientation.

Electronic data-processing now used in acoustic array sonars for long-range viewing and line-scanning could be accomplished optically. Most methods of acoustic holography also fall within this category. The advantage of optical processing is that the complexity and cost do not necessarily increase with larger numbers of array elements as they do with electronic real-time methods.

ACKNOWLEDGEMENT

Prepared for Society of Underwater Technology Conference at Oceanology International, February 1969.

Bibliography

Addresses of relevant organisations are given at the end of this bibliography. Reports suffixed with AD, and most other U.S. government reports, are available from the National Lending Library Boston Spa, Yorkshire, England.

Optical transmission and scattering in water

1. Society of Photo-optical Instrumentation Engineers (SPIE). Underwater photo-optics. 1966.
2. SPIE Underwater photo-optical instrumentation applications. 1968.
3. Jerlov, N. G. Optical oceanography. 1968.
4. Du Pre, E. F. & Dawson, L. H. Transmission of light in water. N.R.L. bibliography no. 20. PB171, 133. 1968.
5. DuPre, E. F. & Dawson, L. H. Transmission of light in water. N.R.L. bibliography no. 20. AD256 765, P 105020. April 1961.
6. Naval Research Laboratory. A bibliography of certain optical properties of liquid water in the infra-red region. N.R.L. bibliography no. 20. 1961.
7. Eastman Kodak Co. Bibliography on underwater photography and photogrammetry.
8. Plessey Co. Attenuation of electromagnetic radiation by sea water. ERL/R 14U. 1962.
9. Petzold, T. J. & Austin, R. W. An underwater transmissometer for ocean survey work. SPIE. 1968.
10. Sanderson, J. A. Optics at the naval research laboratory. Applied Optics, vol. 6 1967. pp. 2029-43.
11. Jenkins, O. & Bowen, O. Transparency of ocean water. J. Opt. Soc. Am. vol. 36. 1946. pp. 617-23.
12. Meredith, R. Unguided optical propagation in the atmosphere and under the sea. I.E.E. Lasers and their applications. 1964.

Natural light

13. Duntley, S. Q. et al. Visibility. Applied Optics, vol. 3. 1964. pp. 582-3.
14. Smith, R. C. A method for determining the contrast of submerged objects. SPIE. 1968.
15. Whitney, O. General law of diminution of light intensity in natural waters and % of diffuse light at different depths. J. Opt. Soc. Am. vol. 31. 1941. pp. 714.
16. Jerlov, N. G. Radiant energy in the Sea. Paris, Inst. Geog. 1960.
17. Clarke, G. L. & Wertheim, G. K. Measurements of illumination at great depths and at night in the Atlantic ocean. Deep-sea Research, vol. 4. 1965. p. 1.
18. Jerlov, N. G. & Piccard, J. Bathyscaph measurements of daylight penetration into the Mediterranean. Deep-sea Research, vol. 5. 1959. pp. 201-4.
19. Burt, W. V. Interpretation of spectrophotometer readings on Chespeake Bay water. J. Marine Res. vol. 14. 1955. p. 47.
20. Duntley, S. Q. Light in the sea. J. Opt. Soc. Am. vol. 53. 1963. pp. 214-33.

Visibility and light penetration

21. Busby, R. F. Undersea penetration by ambient light, and visibility. Science, vol. 158. 1967. pp. 1178-80.
22. Duntley, S.Q. Underwater optics. AD 647, 791. 1966. p. 20.

Transmission

23. Draegert, D. R. et al. Far infra-red spectrum of liquid water. J. Opt. Soc. Am. vol. 56. 1966. pp. 64-9.
24. Curcio, J. A. & Petty, C. C. The near infra-red absorption spectrum of liquid water. J. Opt. Soc. Am. vol. 41. 1951. p. 302.
25. Burt, W. V. Selective transmission of light in tropical Pacific waters. Deep-sea Research, vol. 5. 1957. pp. 51-61.
26. Drummeter, L. F. & Knestrick, G. L. A high-resolution investigation of the spectral attenuation coefficients of water. US Naval Research Lab. report 5642. 1961.
27. Clark, O. & James, O. Selective absorption of light by sea water. J. Opt. Soc. Am. vol. 29. 1939. pp. 43-55.
28. Kinder, F. Underwater light attenuation measurements. SPIE Journal, vol. 4. 1965. pp. 50-4.

Scatter

29. Hulbert, E. O. Propagation of radiation in a scattering and absorbing medium. J. Opt. Soc. Am. vol. 33. 1943. pp. 42-5.

    Dawson, L. H. & Hulburt, E. O. Angular distribution of light scattered in liquids. J. Opt. Soc. Am. Vol. 31. 1941. pp. 554-8.
30. Hulbert, E. O. Optics of distilled and natural water. J. Opt. Soc. Am. vol. 35. 1945. pp. 698-705.
31. Young, O. A note on some laboratory measurements on the transparency of sea water. J. Mar. Res. vol. 5. 1943. pp. 111-5.
32. Jones, O. & Mills, O. Attenuation of light in sea and estuarine waters. J. Mar. Biol. Ass. U.K. vol. 35. 1956. pp. 431-44.
33. Tyler, J. E. Scattering properties of distilled and natural waters. Limnology and Oceanography, vol. 6. 1961. pp. 451-6.
34. Spilhaus, A. F. Observations of light scattering in sea water. AD 610, 126 or N65-23316 MIT Dept of Geol. & Geoph. 1965.
35. Blackburn, P. A. & Leacy, A. C. Private communication. Plessey Co.
36. Sorenson, G. & Honey, R. C. Instrumentation for measuring visibility limiting characteristics of sea water. SPIE. 1968.
37. Gall, O. Measurements to determine the extinction coefficient in the North Sea and English Channel. J. Mar. Biol. Ass. U.K. vol. 28. 1949. p. 757.
38. Parsons, T. R. Suspended organic matter in sea water. Progress in Oceanography, vol. 1. 1963. pp. 205-39.
39. Strickland, J. D. H. Preliminary studies on the estimation of suspended matter in sea water from the air. Fish Res. Bd. Canada, MS report no. 88. p. 21.
40. Beardsley, G. F. Mueller scattering matrix of sea water. J. Opt. Soc. Am. vol. 58. pp. 52-7.

Resolution

41. Green, P. S. Image spreading function in a medium containing discrete isotropic scatterers. J. Opt. Soc. Am. vol. 56. 1966. pp. 607-10.
42. Replogle, F. W. Underwater illumination and imaging measurements. SPIE 1966.
43. Replogle, F. S. & Steiner, I. B. Resolution measurements in natural water. J. Opt. Soc. Am. vol. 55. pp. 1149-51.

Lasers

44. Bibliography of laser applications. AFCRL0223. 1967.
45. Okoomian, H. J. Underwater transmission characteristics for laser radiation. Applied Optics, vol. 5. 1966. pp. 1441-6.
46. Curcio, J. A. & Knestrick, G. L. Transmission of ruby laser light through water. J. Opt. Soc. Am. vol. 53. 1963. p. 514.
47. Knestrick, G. L., Curcio, J. A., Matlock, D. & Templin, H. A. Transmission of coherent and non-coherent light through water. J. Opt. Soc. Am. vol. 54. 1964. p. 1400.
48. Matlock, D. E., Templin, H. A. & Talbert, W. W. Transmission of green laser light through water. Naval Ordance Lab. N65-20605 or NOLTR-64-179 1965.
49. Duntly, S. Q. Scattering and attenuation measurements for a frequency-doubled neodymium laser. Report AD631033.
50. Knestrick, G. L. Comparison of underwater attenuation of laser with non-laser light. NRL 6181.
51. Mutschlechner, J. P. et al. Sea water attenuation measurements with a ruby laser. Applied Optics vol. 2. 1963. pp. 1202-3.
52. Gilbert, G. D. et al. Underwater experiments on the polarization, coherence and scattering properties of a pulsed blue-green laser. SPIE 1968.

Discrimination against scatter

53. Briggs, R. O. & Hatchett, G. L. Techniques for improving underwater visibility with video equipment. Ocean Science and Engineering, vol. 2. 1965. pp. 1284-308.
54. Duntley, S. Q. Principles of underwater lighting. SPIE. 1966.

Pulsed range-gating method

55. Coleman, K. R. High-speed photography. Int. Sci. and Tech. 1964. pp. 40-4.
56. Christie, R. H. Photographic radar. 7th High-speed photography congress. Darmstadt, Helwich.

57. Christie, R.H. Photographic radar. J.Sci.Instr. vol. 43. 1966. pp. 524-7.

58. Neumann, D.B. Precision range-gated imaging technique. JSMPTE vol. 74. pt. 1. 1965. pp. 313-9.

59. Immarco, A. & Oigarden, T. Underwater detection and classification system. SPIE. 1966.

60. Wall, M.R. Underwater viewing. A.E.R.E. Technology of the sea and sea-bed. R5500. H.M.S.O. Vol. 1. 1967. pp. 59-100.

61. Heckman, R. & Hodgson, R.T. Underwater optical range gating. I.E.E.E. Journal of Quantum Electronics, vol. QE-3. 1967. pp. 445-9.

62. Bovill, A.W. & Blackburn, P.A. Initial study of an underwater tv system using pulsed-laser illumination. Plessey Co. ERL/R 79U. 1967.

63. Hodara, H. et al. Laser applications to underwater optics. I.E.E.E. Laser Engineering and Applications. 1967. Paper II-7.

64. Keil, T. et al. Recent underwater range-gated measurements. SPIE 1968.

65. Wall, M.R. Underwater viewing. SPIE 1968.

66. Johnson, N.E. Laser system for underwater observation. Research and Development, vol. 19. 1968. pp. 28-31.

67. Arpishkin, V.M. et al. The application of lasers with regulated pulses for photographing distant objects with selection in regard to the range. 8th High-speed photography congress. 1968. pp. 401-2.

68. Kerpchar, M. & Immarco, A. Theoretical performance and test data of an underwater range-gated tv system. Society of Underwater Technology. Oceanology International 1969.

69. Morton, G.A. & Ruedy, J.E. The low-light level performance of the intensifier orthicon. Advances in Electronics and Electron Physics, vol. 12. 1958. p. 183.

70. Hopmann, W. The image-orthicon in high-speed photography. Advances in Electronics and Electron Physics. vol. 22B. 1966. pp. 1011-9.

71. Weimer, P.K. The image-isocon—an experimental television pickup tube based on the scattering of low-velocity electrons. R.C.A. Review, vol. 10. 1949. pp. 366-86.

72. Mouser, D.P. et al. A practical television tube for low-light levels. Television Society Journal. vol. 11. 1967. pp. 261-5.

73. Advances in Electronics and Electron Physics. vol. 12. 1958, vol. 16. 1961, vol. 22A & B. 1966.

Scanning

74. Anon. Laser tv camera. Electronics Review, vol. 38. pp. 29-30.

75. Martin, R.E. Extended-range underwater viewing systems. SPIE 1966.

76. Kornstein, E. & Wetzstein, H. Blue-green high-powered light extends underwater visibility. Electronics. 1968. pp. 140-50.

77. Wall, M.R. Underwater viewing. A.E.R.E. R5500 H.M.S.O. 1967.

78. Wall, M.R. Optical two-dimensional synchronous-detection high-speed photography. 8th High-speed photography congress. 1968.

79. McManus, R.G. & Chabot, A. Scan-synchronised receiver optimises laser ranging. Laser Focus, 1966. pp. 18-23.

80. I.T.T. Industrial Laboratories. Unique properties of image dissectors. Application note E6.

81. Beyer, R.R. Novel image-dissector camera-tube for surveillance application investigation. Westinghouse. AD653, 855. 1963.

82. Eberhardt, E.H. Signal-to-noise ratio in image dissectors. I.T.T. Industrial Laboratories. Research memo no. 386.

83. Angelbeck, A.W. Application of a laser scanning and imaging system to underwater viewing. SPIE. 1966.

84. Fowler, V.J. & Schlafer, J. A survey of laser beam deflection techniques. Applied Optics, vol. 5. 1968. pp. 1675-82.

85. Aas, H.G. & Erf, R.K. Application of ultrasonic standing waves to the generation of optical beam scanning. J.Acoust.Soc.Am. vol. 36. 1964. pp. 1906-13.

Polarization method

86. Gilbert, G.D. & Pernicka, J.C. Improvement of underwater visibility by reduction of backscatter with a circular-polarization technique. Applied Optics, vol. 6. 1967. pp. 741-6.

87. Lemaire, I.P. & Hodara, H. A review of laser applications to underwater illumination. Lasers et Optique Non-conventionelle. 1967. pp. 120-4.

88. Gilbert, G.D. et al. Improvement of underwater visibility by reduction of backscatter with circular-polarization technique. SPIE. 1966.

Ranging

89. Henkel, R. Laser may light ocean depths to allow precise positioning and mapping. Electronics, 1966. pp. 129-31.

90. Jelalian, A.V. Sea echo at laser wavelengths. Proc. I.E.E.E. vol. 56. 1968. pp. 828-35.

91. Bender, P.L. Laser measurements of long distances. Proc. I.E.E.E. vol. 55. 1967. pp. 1039-45.

92. Lucy, R.F. et al. Precision laser automatic tracking system. Applied Optics, vol. 5. 1966. pp. 517-24.

93. Barnard, T.W. & Fencil, C.R. Digital laser ranging and tracking using a compound axis servomechanism. Applied Optics, vol. 5. 1966. pp. 497-505.

Navigation

94. Henkel, R.W. Laser may light ocean depths to allow precise positioning and mapping. Electronics, 1966. pp. 129-31.

95. Wall, M.R. Laser navigational co-ordinate systems. I.E.R.E. Lasers and Opto-electronics. 1969.

96. Spectra-Physics. Laser instruments for engineering construction. Data sheet.

97. d'Vaz, P. Alignment with a Laser. Optics Technology, vol. 1. 1968. 11-4.

98. Gates, J.W.C. & Bennet, S.J. A confocal interferometer for pointing on coherent sources. J.Sci.Instr.Series 2. vol. 1. 1968. pp. 1171-4.

Communications

99. Wall, M.R. Underwater communications with lasers. British Society of Underwater Technology. 1968.

100. Lytollis, J. Optical communications systems—a survey. Optics Technology, vol. 1. 1968. pp. 1-10.

101. Fried, D.L. & Seidman, J.B. Heterodyne and photon-counting receivers for optical communications. Applied Optics, vol. 6. 1967. pp. 245-50.

102. Champagne, E.B. Optimisation of optical systems. Applied Optics, vol. 5. 1966. pp. 1843-5.

103. Rugieri, N.F. A quantum-statistical analysis of a frequency-modulated laser communication system. Technical report. AD655, 119. 1967.

104. Ward, J.H. A broad bandwidth digital laser communication system. Lasers et Optique Nonconventionelle, vol. 8. 1967. pp. 135-6.

105. Hearn, P. & Berktay, H.O. Underwater telemetry and communications. Society of Underwater Technology. 1969.

106. Burrows, D.W. Cableless underwater television link design and test results. Society of Underwater Technology. 1969.

Particle counting

107. Richards, E.W.T. et al. Particle counting in fast-flowing liquids. Chemistry and Industry. 1969. pp. 22-3.

108. Richards, E.W.T. Private communication.

109. Jerlov, N.G. Particle distribution in the ocean. Swedish Deep-sea Expedition vol. 3. 1958. pp. 73-97.

110. Jerlov, N.G. Optical measurements in the eastern North Atlantic. Goteborg Kungl. Vetensk. Samp. Handl. Ser. B. vol. 8. 1961. pp. 1-39.

111. Suzki, N. & Kato, K. Studies on suspended materials, marine snow, in the sea. Hokkaido University. Bull. Fac. Fish. Part 1 sources of marine snow. vol. 4. 1953. pp. 132-7.

Laser Doppler velocity measurements

112. Rudd, M.J. A laser Doppler velocimeter employing the laser as a mixer oscillator. J. of Sci. Instr. Series 2. vol. 1. 1968. pp. 723-6.

113. Pike, E.R. et al. Measurements of turbulent velocities from the Doppler shift in scattered laser light. J. of Sci. Instr. Series 2. vol. 1. 1968. pp. 727-30.

114. Botcherby, S.C. Private communication. Decca Radar Co.

115. Rudd, M.J. A new theoretical model for the laser Dopplermeter. J.Sci.Instr.Series 2. vol. 1. 1968 pp. 55-8.

116. Goldstein, R.J. & Hagen, W.F. Turbulent flow measurements utilizing the Doppler shift of scattered laser radiation. Plysics of Fluids, vol. 10. 1967, pp. 1349-52.

117. Foreman, J.W. et al. Laser Doppler velocimeter for measurement of localised flow-velocity on liquids. Proc. I.E.E.E. vol. 54. 1966. pp. 424-5.

118. Goldstein, R.J. & Kreid, D.K. Measurement of laminar flow development in square duct. Journal of Applied Mechanics, vol. 34. 1967. pp. 813-8.

119. Drinkwater, J.W. The measurement of ship performance. J.Sci.Instr. vol. 44. pp. 702-8.

Holography

120. University of Michigan. Introduction to optical data processing. Engineering summer conferences. 1966 & 1967.

121. Leith, E.N. Holography. University of Michigan Engineering Summer Conferences. vol. 1. ch. 4.

122. Redman, J.D. et al. The use of holography to make truly three-dimensional X-ray images. Nature, vol. 220. 1968. pp. 58-60.

123. Redman, J.D. Holographic visual displays. Non-destructive Testing, vol. 1. 1968. pp. 360-2.

124. Buzzard, R.D. Description of three-dimensional schlieren system. High speed photography congress. 1968.

Particle recording

125. Knox, C. Holographic microscopy as a technique for recording dynamic microscopic subjects. Science, vol. 153. 1966. pp. 989-90.

126. Gates, J.W.C. Holography with scatter plates. J.Sci.Instr.Series 2. vol. 1. 1968. pp. 989-94.

127. Thompson, B.J. Particle size examination. University of Strathclyde. Engineering uses of holography. 1969.

128. Thompson, B.J. et al. Application of hologram techniques for particle size analysis. Applied Optics, vol. 6. 1967. pp. 519-26.

129. Du Bellay, G.G. Application of holography to microscopic objects. N67 37560.

130. Redman, J.D. & Lowe, M.A. The use of holography to measure the position and velocity of rapidly moving objects. High-speed photography. congress. 1968.

Vibration analysis

131. Powell, R.L. & Stetson, K.A. Interferometric vibration analysis by wavefront reconstruction. J. Opt. Soc. Am. vol. 55. 1965. pp. 1593-8.

132. Stetson, K. A. & Powell, R. L. Interferometric hologram evaluation and real-time vibration analysis of diffuse objects. J. Opt. Soc. Am. vol. 55. 1965. pp. 1694-5.

133. Powell, R. L. The measurement of vibration by holography. University of Strathclyde. Engineering uses of holography. 1969.

134. Stetson, K. A. Vibration measurement by holography. University of Strathclyde. Engineering uses of holography. 1969.

135. Grant, R. M. & von Winkle, W. A. Interferometric holography as a tool for the study of fluxures in active sonar transducers. Lasers et Optique Non-conventionelle, 1967. pp. 37-43.

136. Archbold, E. & Ennos, A. Techniques of hologram interferometry for engineering inspection and vibration analysis. University of Strathclyde Engineering uses of holography. 1969.

137. Wall, M. R. The form of holographic vibration fringes. University of Strathclyde. Engineering uses of holography. 1969.

138. Redman, J. D. Holographic velocity measurement. J. Sci. Instr. vol. 44. 1967. pp. 1032-3.

Optical information processing

139. Redman, J. D. Processing information with light. Science Journal, vol. 4. pp. 51-6.

140. Vander Lugt, A. Spatial filtering part 1. University of Michigan. Engineering summer conferences, vol. 1. ch. 2. 1966 & 1967.

141. Vander Lugt, A. Practical considerations for the use of spatial carrier-frequency filters. Applied Optics, vol. 5. 1966. pp. 1760-5.

142. Vander Lugt, A. Spatial filtering part 2. University of Michigan. Engineering summer conferences, vol. 1. ch. 3. 1966 & 1967.

143. Leith, E. N. Processing radar data. University of Michigan. Engineering summer conferences, vol. 1. ch. 6. 1966 & 1967.

144. Ditchburn, R. W. Youngs eriometer. In Light, ch. 6. 23 Blackie.

145. M.I.T. Press. Optical and electro-optical information processing. 1965.

146. Metherell, A. F. et al. Introduction to acoustical holography. J. Acoust. Soc. Am. vol. 42. 1967. p. 733.

147. Halstead, J. Ultrasound holography. Ultrasonics, vol. 6. 1968. pp. 79-87.

148. Aldridge, E. E. Ultrasonic holography as an extension to C-scan. A.E.R.E. M1921.

149. Mueller, R. K. Real-time acoustic holography. University of Strathclyde. Engineering uses of holography.

ADDRESSES

British Society of Underwater Technology,
1 Birdcage Walk, London, S. W. 1.

Eastman Kodak Co., Commercial & Industrial
Markets Division, 343 State Street, Rochester,
N. Y. 14650, U.S.A.

Naval Ordnance Laboratory, White Oak,
Maryland, U.S.A.

S.P.I.E., 216 Avenida del Norte, P.O. Box 288,
Redondo Beach, California 90277, U.S.A.