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UNDERWATER LASER SYSTEMS

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INTRODUCTION

There are several instances where the use of optical systems under water offer advantages over conventional sonar techniques. A prime example of this is laser hydrography [1] or laser depth sounding where an airborne laser system is used to map the sea bed in coastal regions. The advantage here is that the laser system is capable of much higher data acquisition rates than sonar thereby making it practical to survey very long coastlines in reasonable time. A second example is television recording using a short pulse laser as light source. Such systems offer improved resolution over sonar.

Because of absorption, electromagnetic radiation propagating through water suffers extremely high attenuation in all regions of the spectrum except three narrow bands. These bands are firstly the gamma ray region and secondly, at the opposite end of the spectrum, the extremely low frequency (ELF) region where wavelengths are typically several kilometres. In addition there is also a minimum in the attenuation curve in the blue/green part of the visible region between about 450nm and 550nm and it is in this region that this paper will concentrate.

The paper is intended to be an overview of the underwater uses and techniques of lasers which operate in the blue/green part of the spectrum and as such we will discuss lasers such as the frequency doubled Neodymium-YAG, the Raman-shifted Xenon-Chloride lasers and also Mercury Bromide lasers. Also the systems in which the above mentioned sources can be employed, such as range-gated lidar, enhanced imaging and communications will be discussed.

Before describing these systems the propagation of laser light through natural sea water will be discussed.

LASER PROPAGATION

The attenuation of light in water is a result of not only absorption but also scattering [2]. Absorption, which can be considered as a pure loss since absorbed photons are not re-emitted, is due to the water molecules themselves and also dissolved substances. Scattering on the other hand, whilst not causing a loss of photons, redistributes energy and is dominated by suspended particulates whose size is comparable to the wavelength of the light. The scattering is therefore reasonably well described by Mie theory [2]. If we consider a narrow beam of light of irradiance E_0 the irradiance after the beam has propagated a distance R is given by: [3]

$$E(R) = E_o \exp(-cR) \tag{1}$$

where c is called the beam attenuation coefficient and is the sum of the absorption coefficient (a) and scattering coefficient (b).

Defining the Volume Scattering function $\beta(\theta)$ as being the scattered intensity in the direction θ per unit volume, normalised to the incident irradiance E, i.e.,

$$\beta(\theta) = \frac{dI(\theta)}{E\ dV}\ m^{-1}\ Sr^{-1} \tag{2}$$

then the scattering coefficient b is given by:

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta\ d\theta\ m^{-1} \tag{3}$$

The volume scattering functions of various water types are shown in figure 1. The highly forward scattering is very much in evidence from the curves.

The attenuation law described by equation (1) is strictly relevant if the receiver used to detect the laser beam has an infinitesimally small field of view. In other words any photons which are scattered at any angle greater than zero is lost to the system. In practice a receiver will have a finite field of view and a finite diameter and therefore will be able to detect some of the scattered light. In the limit of a receiver with a field of view of 180° the only losses will be due to absorption plus scattering at angles greater than or equal to 90°. That is backscatter, and the backscatter coefficient is given by:

$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin\theta\ d\theta \tag{4}$$

The total attenuation coefficient γ in this case is therefore given by:

$$\gamma = a + b_b \tag{5}$$

In any real system used to directly detect laser light under water the effective attenuation will lie somewhere between the two extremes given by (1) and (5).

Another important concept is that of the diffuse attenuation coefficient or irradiance attenuation coefficient. If E (Z) is the solar irradiance at a depth Z under water then the diffuse attenuation coefficient K_d is given by:

$$E(Z) = E(0) \exp(-K_d Z) \qquad (6)$$

K_d has been measured by many workers [3] worldwide by using photometers to measure the sunlight as a function of depth.

The spectral variation of the diffuse attenuation coefficient is shown in figure 2. These measurements are due to Jerlow [2] and are used to classify water types. The clearest water is obviously that which has the lowest value of K_d and according to the Jerlov classification is called Type 1 ocean water, having a minimum value of K_d of $0.02m^{-1}$ occurring at a wavelength of approximately 480nm. Moving toward the coastal type waters the minimum value of K_d increases to approximately $0.1m^{-1}$ at a wavelength of about 550nm.

From figure 2 it can be seen that attenuation except in the clearest ocean water (Type 1) is very high. This obviously implies that the useful range of typical underwater systems is limited to values of several hundred metres or less.

Although the use of an attenuation coefficient is sufficient in some cases to define a system's performance, in others such as partial intercept lidar it is important to know how the beam spreads with propagation distance. Although there are analytic solutions of the radiative transfer equation which give the beam spread function, they usually involve severe approximations and are therefore of limited application in systems design. A much more powerful technique, especially in situations where photons are scattered many times before detection, is the Monte Carlo method. Monte Carlo techniques applicable to underwater propagation of laser light are discussed in reference [4].

SYSTEMS

Bathymetry

The above brief description of the propagation of light through sea water has shown that ranges are limited compared with sonar. One optical system for which a lack of long range performance is not a disadvantage is laser bathymetry of coastal waters. In such systems an airborne pulsed laser is directed through the water column and an optical receiver detects pulses reflected from the sea surface and the sea bed. The depth of the water column is obtained by measuring the time delay between the two return pulses. It has been estimated that a laser based system can survey 2000 square nautical miles annually, an area equal to that now being surveyed by 20 hydrographic launches [1].

Systems such as AOL (Airborne Oceanographic Lidar) and HALS (Hydrographic Airborne Laser Sounder) have been operated in the United States from as early as 1977. There are also laser hydrography systems operating in Australia (LADS: Laser Airborne Depth Sounder) and in Canada.

All of the above systems use frequency doubled Neodymium-YAG lasers producing short (10ns) pulses of 10^6W peak power. The maximum depth measurable by each of these systems depends predominantly on the water clarity but is typically 30-50m. This range is given by the so-called lidar range equation which is given by:

$$P_R = C.P_T \exp(-2n\ K_d\ D) / (n_w\ H + D)^2 \qquad (7)$$

where P_R, P_T are the received and transmitted powers
D is the depth of water
H is the height of the receiver above the water
n_w is the refractive index of sea water (1.33)
K_d is the diffuse attenuation coefficient
n is a factor which accounts for temporal stretching of the pulse because of multiple scattering

The constant C in equation (7) contains such terms as the reflectivity of the sea bed, which is typically a few percent, and also the transmitter and receiver transmission factors as well as geometrical factors.

It is evident from equation (7) that, in addition to the exponential attenuation factor, the received power is inversely proportional to the square of the range. This is due to the fact that the beam is totally intercepted by the target (i.e. sea bed). In cases where lidar is used to detect objects which are smaller than the beam size the received power depends inversely on the fourth power of the range, thus reducing the useful range of such systems.

Communications
A second important application of blue/green lasers is underwater communications, particularly satellite to submarine communications [5]. Several conceptual schemes exist for this system. The first of these employs a laser such as a Mercury Bromide, or a Raman Shifted Xenon chloride laser on the satellite in geostationary orbit to transmit, over wide areas of the ocean, to a submarine. The message is transmitted to the satellite via conventional radio link. An alternative scheme has the laser transmitter on land being directed at a satellite with a large mirror attached. In both schemes the laser pulse must propagate through the atmosphere as well as the sea. This introduces a power loss due to atmospheric scattering and turbulence and also produces considerable pulse stretching if the signal passes through clouds. However, in contrast to the bathymetry case, attenuation in the clear ocean is relatively low and only a one-way propagation is required which means that data

can be transmitted through several hundred of metres of water.

The optical receivers for communication must be extremely sensitive with wide field of view and narrow optical bandwidth to discriminate against solar background noise.

Enhanced Imaging

Underwater photography and television recording generally have very limited working distances if natural lighting is used because of attenuation. If artificial lighting is used to extend the useful range then backscatter from particulate matter into the camera can cause a severe reduction in image contrast.

The amount of light backscattered into the receiver depends on the value of the volume scattering function evaluated at 180° and also on the flash duration τ. Now if the target being viewed has a reflectivity ρ then it can be shown that the image contrast ratio C is given by: [6]

$$C = \frac{\rho}{\pi.\tau.\beta(180^\circ)} \tag{8}$$

One means of improving the contrast ratio is to use intense short pulse laser instead of normal flash. Backscatter from the water between the target and camera can be eliminated by the technique of range gating. Here the camera shutter is kept closed until the laser pulse being used to illuminate the target reaches the target. Because typical ranges are less than 100m, shutter speeds and delays must be of the order of a few hundred nanoseconds or less. British Aerospace are currently developing an underwater camera system which is electronically range gated by applying a biasing voltage to the anode of an image intensifier. Removal of the bias voltage allows the intensifier to operate at peak gain.

In addition to the above important systems there are many systems which use lasers for oceanographic measurements such as water salinity, temperature and particulate content. A review of such systems can be found in reference [1].

LASER SOURCES

The type of blue/green laser suitable for each of the systems described above, and other systems, is determined usually by the water type. That is the operating wavelength is fixed so that the attenuation is minimised. Other factors may, however, influence the choice of laser, such as the need for a very high repetition rate.

Nd-YAG

As stated in the discussion on Laser Hydrography, for coastal applications the most suitable laser is the frequency doubled Neodymium-YAG [7] which gives an output at 532nm. The main Neodymium laser is a solid state device with tri-valent Neodymium ions imbedded in an Yttrium Aluminium Garnet crystal (YAG). The laser output from the Nd-YAG is in the infra-red region at 1.06μm and this is doubled with an efficiency of typically 20% by using a second crystal CDA (Cesium Di-hydrogen Arsenate). The laser is optically pumped by flashlamps and the crystal is water-cooled to remove excess heat. Pulses of several megawatts peak power and 20ns duration can be generated without difficulty at a repetition rate of 10-20Hz. Repetition frequencies greater than this are difficult to generate in solid state lasers because of the problem of overheating of the laser crystal.

Raman Shifted Xenon Chloride Laser

This type of device is known as an EXCIMER [8] laser and is one of a family of powerful rare gas halide lasers which emits in the ultraviolet between 193nm and 350nm. XeCl can be excited in a gas discharge, operated at room temperature using a high pressure gas mix of Xe and HCl and outputs of up to 5J in pulses of 100ns duration at repetition rates of up to 1kHz have been demonstrated. The output from the laser is not at a wavelength suitable for underwater systems but it can be converted from 308nm to either 459nm or 500nm by using stimulated Raman scattering in atomic and molecular gases. The laser beam is passed into a cell containing a Raman active medium which absorbs the UV radiation, undergoes a Raman shift, and emits a photon of lower frequency. Lead vapour at a temperature of 1200°C can be used to produce a single step shift to 459nm with 50% efficiency. Molecular hydrogen is used to shift the output to 500nm via three consecutive absorption/emission events.

Mercury Bromide Laser

Both of the lasers discussed above need to have their fundamental output frequency shifted to the blue/green region. One laser which lases directly in the blue/green is the Mercury Bromide laser [9]. This is somewhat similar to the Xenon Chloride device in that it is a gas discharge laser operating by dissociation of stable Mercury Bromide ($HgBr_2$) to produce emission on two peaks at 502nm and 504nm. Although it is a very efficient device it is necessary to operate the device at 180°C in order to maintain sufficient vapour pressure of $HgBr_2$. Pulse energies of several joules at repetition rates of up to 100Hz are obtainable from these lasers. At present the Laser Systems Department of British Aerospace are building a Mercury Bromide device for potential use in underwater systems.

Other Systems

Although the three devices discussed above are certainly the most important for underwater systems there are many more lasers which produce output in the right wavelength range but for various reasons such as low power or limited lifetime are not suitable for incorporating into systems. These include flashlamp pumped visible dye lasers and copper vapour lasers.

Table 1 shows a comparison of these lasers together with the three discussed above and also some others.

CONCLUSION

The purpose of this paper was to inform the reader of some of the underwater optical systems using lasers as the optical source. Although the discussion was necessarily brief and therefore limited to basic concepts only, it is hoped that this purpose was achieved.

To summarise then: the severe attenuation of light in sea water which is a result of absorption and scattering by particulate matter causes the useful range of laser systems such as lidar or communications to be limited to hundreds of metres. There are instances however where the limited range performance is not detrimental and an optical system offers advantages over sonar. Several such examples, namely laser hydrography, strategic communications and enhanced imaging were discussed.

Table 1. Comparison of some blue/green lasers

Laser	Wavelength nm	Pulse Energy mJ	Pulse Width ns	Pulse Repetition Hz	Efficiency %
Frequency doubled Nd:YAG	532	5-500	15	10-20	0.5
Excimer: XeCl etc.	459 500	400	30	100	<1
HgBr	502	1000	20-350	100	1
Flashlamp pumped dye	Tunable	50-500	500	10-500	.5
Copper vapour	511	40	1.0	5000	1
Argon ion	488 514	10^4	1	10-100	<0.1
Iodine Monofluoride	479 485 490 497	15	<1	1	10^{-4}

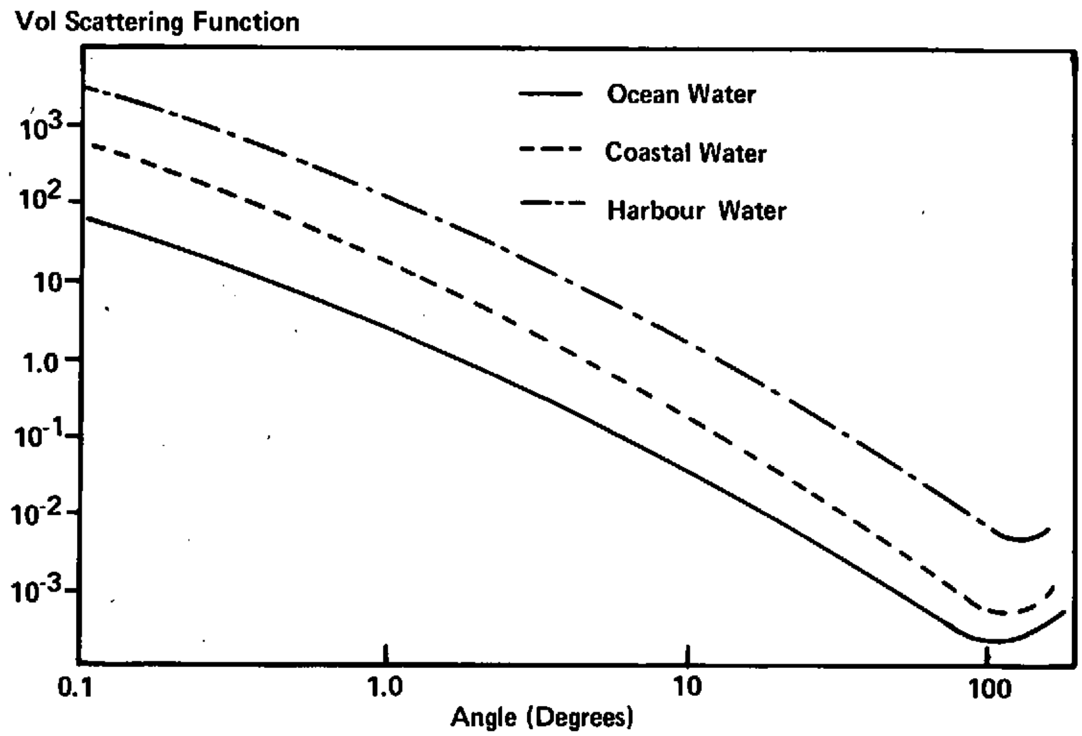

Figure 1. Volume scattering functions (from Gordon et al, [3])

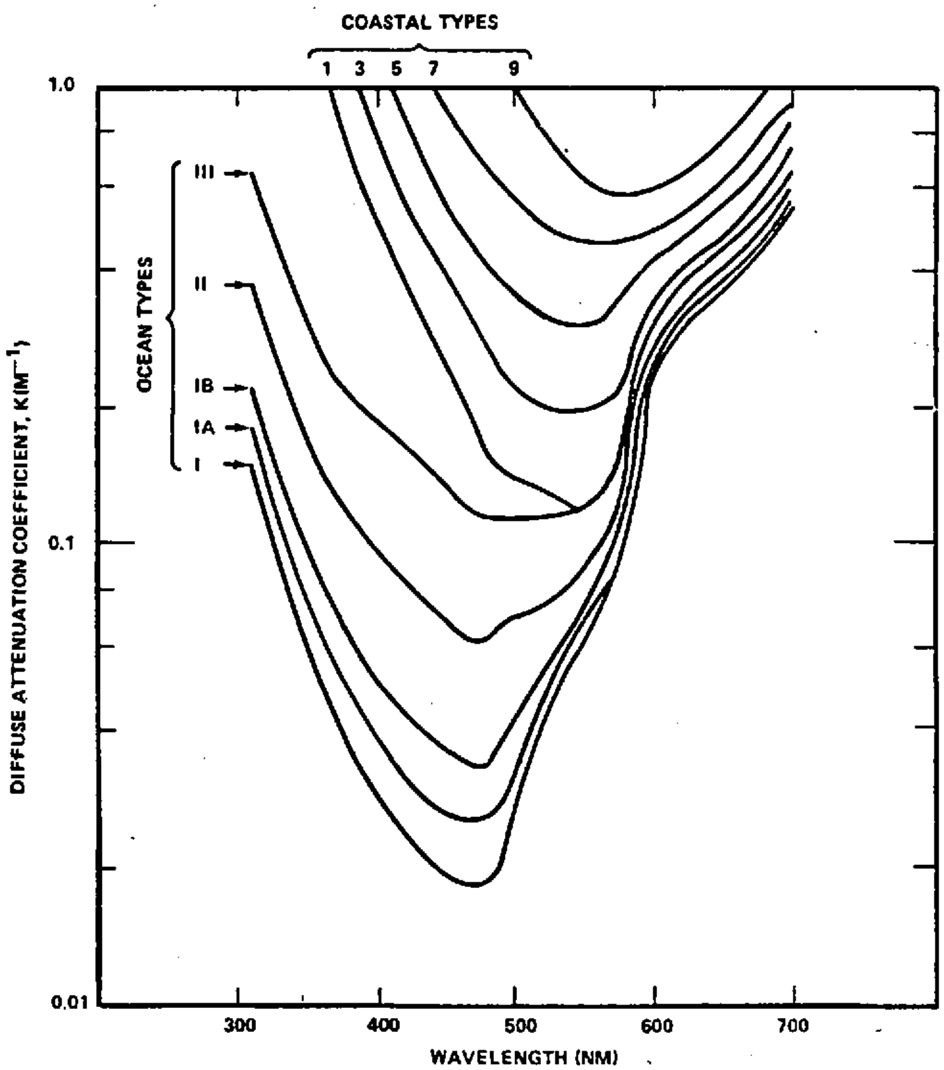

Figure 2. Diffuse attenuation coefficients for ocean waters (from Jerlov [2])

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