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Laser System Usage in the Marine Environment: Applications and Environmental Considerations

B. Swope

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

STUDY OUTLINE AND GOALS

This report assesses potential environmental impacts of laser systems on organisms found living in the marine environment. To accomplish this objective, the major laser systems used by the Navy in a marine setting were defined, Environmental Impact Statements (EISs) for various ranges were reviewed, and naval researchers were queried to determine the most prominent laser system usage. Once the predominant laser systems were identified, a list of biological groups that may be affected was generated. To determine the potential impact of a laser system to an organism in the marine environment, an assessment pathway with the following four components was developed: (1) laser system specifications, (2) exposure potential**, (**3) damage thresholds, and (4) potential impacts. Literature was reviewed for information related to both exposure potential as well damage thresholds and expected impacts. As a starting point, the most conservative, or worst case scenario, values for laser system outputs and exposure potential were used in evaluating biological impact, e.g., direct exposure with no energy attenuation.

RESULTS

LiDAR (Light Detection And Ranging) is the most prominent laser system used in the marine environment. LiDAR has a broad range of applications, including mine detection, surveillance, mapping, and the assessment of various oceanographic data. Although LIDAR has a broad range of applications, the specifications of various laser systems are similar. LiDAR systems generally operate in the blue/green spectrum with a wavelength of 532 nm generated from a Nd:YAG (neodymium-doped yttrium aluminum garnet) laser. To assess potential impacts to marine life, output parameters were chosen based on a LiDAR system used by a collaborative research group consisting of the U.S. Army Corps of Engineers (USACOE), the U.S. Naval Meteorology and Oceanography Command, and the National Oceanic and Atmospheric Administration (NOAA). Other prominent laser systems include laser line scan (LLS) and those used in communications. These other systems are not as widely used and generally have beams with a greater divergence, resulting in lower energy per given area. Therefore, based on usage and system output parameters, LiDAR is the best representative system for assessing environmental impacts.

Several major biological groups may be impacted by laser systems, including marine mammals, sea turtles, plankton, and benthic communities. The exposure mechanism that may cause the greatest damage varies among these groups. Ocular exposure represents the most critical exposure route for marine mammals and sea turtles, while damage to plankton and benthic groups would be more systemic. The amount of laser energy an organism is exposed to is a function of the organism's location in the water column from an above water source, or distance from the laser when the source is underwater. Laser energy attenuates rapidly through the water column, thus the higher in the water column (shallower), or closer to the source, the greater the amount of energy exposure. Direct uninhibited ocular exposure could only occur during the unique scenario when a marine mammal or sea turtle surfaces at the same time a LiDAR beam passes.

Each major biological group was assessed for damage potential from the various laser systems, although focus was primarily on LiDAR. Marine mammals and sea turtles have the greatest damage potential due to direct ocular exposure when the animal has surfaced, with damage most likely occurring to the retina. For a given laser exposure, the amount of energy reaching the retina depends on specific dimensions of the eye and the focusing ability of the animal, resulting in a species-specific damage potential. Nineteen marine mammal and sea turtle species were assessed for damage potential based on their specific eye/vision parameters and the laser output from the representative LiDAR system. None of the animals were predicted to incur any damage from a direct, above surface, laser exposure. The results of this study support that LiDAR systems designed to meet human safety standards will be safe to marine mammals or sea turtles that may be exposed, and actually could withstand laser exposures from more powerful systems. Additionally, the likelihood of exposure is estimated to be a rare event based on the number of annual training hours these laser systems are used and marine mammal/sea turtle densities found in the training areas, combined with the likelihood of an animal surfacing and receiving subsequent eye exposure. The other major biological groups also are not likely to be affected negatively by the various laser systems used, based primarily on the rapid attenuation of laser energy in the water column and the overall low-energy output of the systems.

CONSLUSION AND RECOMMENDATIONS

Laser systems play an important role in a diverse range of Navy activities, including mine detection, mapping, oceanography, and communications. The continuation of research and development efforts on underwater laser systems will further enhance Navy capabilities within these activity areas. It is critical to ensure a timely transition from research and training applications to real-world field settings. The potential for lasers to negatively impact organisms in the marine environment are low. This assessment primarily is based on the energy levels of the lasers being used and the minimal exposure potential to marine organisms. The findings within this report should help streamline Environmental Impact Statements (EISs), Programmatic Environment, Safety and Occupational Health Evaluations (PESHEs), and other regulatory processes by providing data on the environmental safety regarding the use of laser systems within the marine setting. The information in this report covers all geographic locations and is relevant to current and new systems that use the operating parameters specified in this report. Additionally, the methodology for assessing damage potential for the various biological groups can be used as a template for new systems with different operating parameters.

ACRONYMS AND ABREVIATIONS

ALMDS	Airborne Laser Mine Detection
ANSI	American National Standards Institute
CHARTS	Compact Hydrographic Airborne Rapid Total Survey
DOM	Dissolved Organic Matter
EIS	Environmental Impact Statements
ESOH	Environmental, Safety and Occupational Health
JALBTCX	Joint Airborne Lidar Bathymetry Technical Center of Expertise
LED	Light Emitting Diode
LiDAR	Light Detection and Ranging
LLS	Laser Line Scan
MPE	Maximum Permissible Exposure
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NEPA	National Environmental Protection Act
NOAA	National Oceanic and Atmospheric Administration
PAR	Photosynthetically Active Radiation
PESHE	Programmatic Environment, Safety and Occupational Health Evaluations
R&D	Research and Development
RF	Radio Frequency
SEADEEP	Submarine-Enabling Airborne Data Exchange and Enhancement Program
SHOALS	Scanning Hydrographic Operational Airborne LiDAR Survey
UAV	Unmanned Aerial Vehicle
USACOE	U.S. Army Corps of Engineers
UUV	Unmanned Undersea Vehicle
UV	Ultraviolet

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1. INTRODUCTION

The Navy currently uses, and is continuing to develop, laser technology applied in an underwater marine environment. This technology primarily is used for communication, surveillance, and mine detection. As new technologies are transferred to the Fleet through the acquisitions process, it is necessary to identify and mitigate environmental, safety, and occupational health (ESOH) risks associated with the emerging systems. ESOH risks need to be addressed in compliance documentation related to PESHEs in the acquisition process, and National Environmental Protection Act (NEPA) compliance, which includes preparing EISs for proposed Navy actions. Currently, EISs use general information to assess the risk of laser activity in the marine environment. Scientifically defendable technical data are needed to develop Navy-wide environmental policies for performing EISs with laser activity in marine environments.

2. MATERIALS AND METHODS

This report represents a comprehensive literature review of the most recent available data related to laser exposure and damage thresholds for organisms found in the marine environment. A multi-step approach was used to address the questions outlined in this project.

1. Define Laser Systems: The first step was to identify the various laser systems employed on Navy at sea ranges. This step was completed by reviewing EISs for ranges throughout different eco-regions. Additionally, Navy researchers were queried for input regarding the use of current or future laser systems.
2. Define Biological Communities: Based on the characteristics and applications of the laser systems identified, biological groups that were potentially impacted were determined.
3. Define a Means to Assess Environmental Impact: Once the potentially affected biological communities were defined, a means to assess each specific community was identified. This effort included the development of an assessment pathway based on the laser systems output power and a review of available literature on both the likelihood of exposure, and expected impacts based on exposure.
4. Evaluate Potential Impacts: The final step in the approach was to synthesize the results to determine the overall potential for environmental impact from the various laser systems.

3. BACKGROUND: APPLICATIONS AND LASER SYSTEMS

Laser usage in the marine environment applies to a range of technology used for a diverse scope of applications. Various applications are discussed in further sections with examples of the specific laser technologies used.

Several parameters of laser systems that are optimized for use in the marine environment include the following:

- **Wavelength** is the distance between the peaks of two consecutive waves, and for light is measured in nanometers (nm). Wavelength is related to the “color” of light. Visible light generally falls between 400 to 700 nm, while infrared is >700 nm (up to 1 mm) and ultraviolet is < 400 nm (down to 10 nm).
- **Frequency** is a measurement of how often a laser pulse is emitted. Frequency is measured in hertz (Hz), which corresponds to the number of cycles per second.

- **Pulse width, or pulse length**, is the duration the laser pulse is emitted and measured in nanoseconds (ns).
- **Total emitted energy** is related to how powerful the laser pulse is or how much energy is given off, and is measured in millijoules (mJ) or joules (J).
- **Beam footprint/ Divergence** applies to aerial systems, and is the diameter of the laser beam when it hits the water (or ground) surface and is measured in meters squared (m^2) or centimeters squared (cm^2). The beam footprint measurement assumes the system will be flown at a predetermined constant altitude. Alternatively, beam divergence is a measure of the increase in beam diameter from the source of the laser pulse. Beam divergence is an angular measurement given in milliradians (mrad).

3.1 MAPPING, MINE DETECTION, AND SURVEILLANCE

The application of laser systems to detect items at and below the water's surface has been widespread for several decades, with new applications still being identified (Guenther, 1985; LaRocque and West, 1990). Systems were used in various oceanographic functions, including assessment of hydrographic parameters, phytoplankton fluorescence, near-shore coastal bathymetry mapping, and fish surveys (Hoge and Swift, 1983; Brown et al., 2002; Churnside, Wilson, and Tatarskii, 2001). The technology also has been applied for the detection of mines at and below the water's surface (DoN, 2008a,b). More recently, the technology was applied to initial surveillance of riverine systems prior to troop deployment.

3.1.1 LiDAR

Light Detection and Ranging (LiDAR) is an optical remote sensing technology. The system works by transmitting laser pulses towards an object of interest and then measuring the return pulse signal. The objects distance, or range, can be determined by the time it takes for the pulse to return, while other information can be gained from the return signal strength. The LiDAR system generally is mounted on an aircraft (airplane, helicopter, or unmanned aerial vehicle) and flown over the area mapped or targeted. The system consists of a laser transmitter and a sensor receiver, and can be paired with other technology to provide an enhanced assessment of the environment being surveyed.

LiDAR systems used in the marine environment use lasers in the blue/green range that offer the greatest penetration through the water column and generally are set to 532 nm using an Nd:YAG laser. Additionally, a near infrared laser (1064 nm), for which there is little or no penetration, is used to determine a baseline sea surface position relative to the aircraft. A general schematic of an airborne LiDAR system is shown in Figure 1. LiDAR systems employed for mapping, detection, and surveillance can achieve a high spatial and depth resolution. To achieve this resolution, numerous pulses need to be sent out, which correlates to smaller pulse widths (6 to15 ns) and higher frequencies (~3000 Hz).

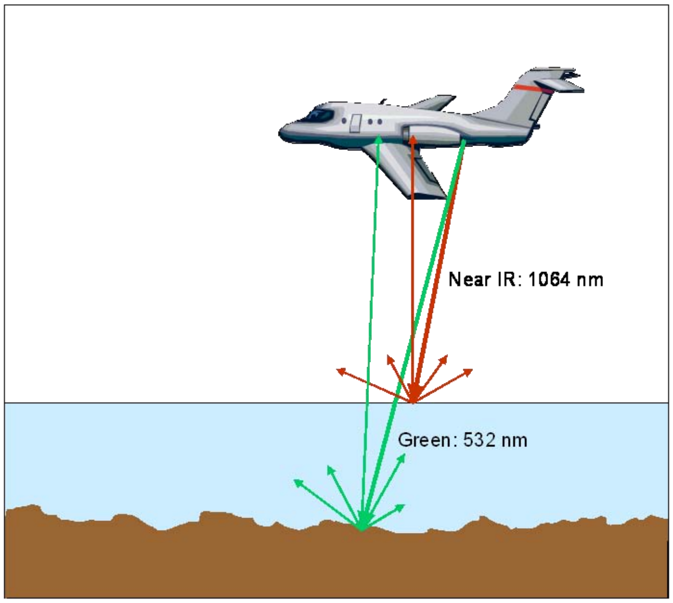

Figure 1. General schematic of LiDAR system deployed from an aircraft.

The effective depth of LiDAR depends on transmission through the water column. The transmissivity of the laser is dependent on a host of parameters, including weather (clouds, sun angle), surface conditions (ripples, waves), and turbidity (suspended sediment, plankton). Generally, LiDAR is most effective for bathymetry mapping in near-shore and coastal areas, surface/subsurface mine detection, as well as assessment of near-surface hydrographic and biological data. The spatial range bathymetry mapping that can be used is a function of the effective depth for the system. Therefore, the distance offshore LiDAR that can be used for bathymetric mapping is greatly influenced by water clarity and slope of seafloor, where the greatest range would be experienced in clear water with a gradual slope.

Generally, LiDAR is effective to depths three times the Secchi depth, or visible depth, and on average, would be approximately 20 m (Irish, McClung, and Lillycrop, 2000). Bathymetry mapping will therefore be confined to the near shore and coastal regions to depths of approximately 20 m, with the corresponding spatial range being highly site-specific. LiDAR used for mine detection or collection of near-surface hydrographic/biological data can be used in any geographic area with sufficient water clarity. The specific application of LiDAR will determine the most appropriate system to use.

Two examples of LiDAR systems currently used for mine detection and bathymetry/oceanographic purposes include the ALMDS (Airborne Laser Mine Detection System) and the SHOALS-3000.

The ALMDS detects and classifies floating and near-surface moored mines and is designed to be mounted on the MH-60S helicopter (DoN, 2008b, Figure 2). The ALMDS is one tool in a suite of Organic Airborne Mine Counter Measure (OAMCM) technology with the goal of clearing safe passage through a minefield for ships or amphibious landing craft (DoN, 2008b). The SHOALS-3000 (manufactured by Optech) is the LiDAR component of the CHARTS (Compact Hydrographic Airborne Rapid Total Survey) system used by the Joint Airborne LiDAR Bathymetry Technical Center of Expertise (JALBTCX). JALBTCX consists of researchers from the U.S Army Corps of Engineers (USACOE), the U.S. Naval Meteorology and Oceanography Command, and the National Oceanic and Atmospheric Administration (NOAA). The JALBTCX mission is to perform operations, research and development in airborne LiDAR bathymetry and complementary technologies to support the coastal mapping and charting requirements (JALBTCX, 2009).

The SHOALS-3000 uses a Nd:YAG laser that generates a fundamental near infrared (1064-nm) beam as well as a frequency-doubled blue/green (532-nm) beam. The co-aligned laser pulse is fired down at the water and the 1064-nm beam is reflected by the water's surface while the 532-nm beam penetrates the water column and is reflected by the seafloor. The combination of these data streams allows for the accurate bathymetric measurements and near-shore mapping.

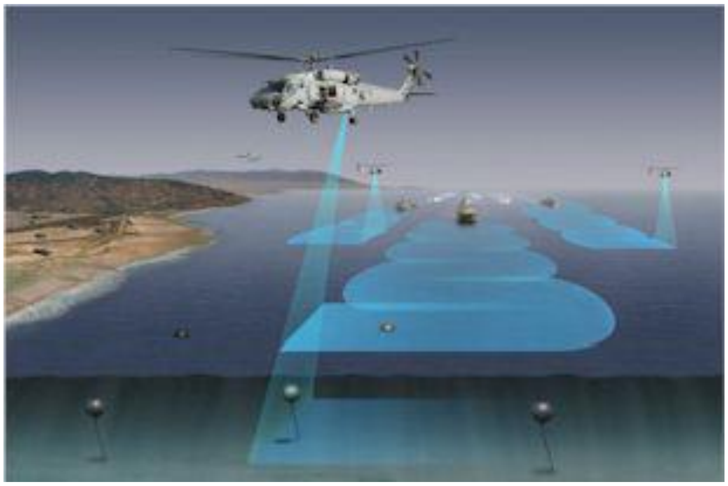

Figure 2. MH-60S Helicopter using ALMDS for mine detection.

The ALMDS and SHOALS-3000 are two predominant examples LiDAR technology used by the Navy in various application settings. Although application of the LiDAR technology and the overall designs may vary, LiDAR systems are fundamentally similar in the output parameters. Table 1 shows the output parameters for the SHOALS-3000 system and will be used as a representative LiDAR system in subsequent sections for assessing environmental impacts.

Table 1. Output parameters for the SHOALS-3000 LiDAR system.

System Name	Wavelength (nm)	Frequency (Hz)	Pulse Width (ns)	Total Emitted Energy (mJ)	Spot Size (cm^2)	Energy at Surface (J cm^{-2})
SHOALS-3000	532	3000	6	7.5	31416	2.39E-07

3.1.2 Laser Line Scan

Laser line scan (LLS) is a technique used for viewing the seafloor or other underwater targets. The system operates fully submerged, and is generally part of a towed array or moving platform such as an unmanned undersea vehicle (UUV) (Figure 3). LLS systems are typically deployed between 3 and 9 meters above the seafloor (NOAA, 2001). LLS provides high-resolution images of the seafloor or benthic habitat in real time and is a survey technique which can be effective in deeper water outside the depth range of LiDAR (Jaffe, Moore, Mclean, and Strand, 2001). The system works by transmitting laser beams towards the seafloor and illuminating individual spots in a 70° sector. An optical sensor builds an image from the numerous spots, and then the system displays the information as a two-dimensional image in real time (Moore and Jaffe, 2002). The wavelength of the LLS generally is 532 nm. LLS has been employed in seafloor mapping as well as furthering the capability of underwater mine detection.

Figure 3. UUV using LLS.

3.2 COMMUNICATIONS

Laser technology used for communications underwater primarily focuses on the needs of the submarine community. Traditionally, submarines must be at or near the surface, with antennae above the water to achieve two-way communication due to the inability of radio frequency (RF) transmission in saltwater. Recent technological advances in achieving two-way communication while submarines at depth (~400 ft) and speed (25 knts) include the use of floating antennas and buoy systems, acoustic systems, and laser systems (Qpeak, 2007). The primary candidate for laser communications comes out of the Submarine-Enabling Airborne Data Exchange and Enhancement Program (SEADEEP). The SEADEEP laser system enables communication between aircraft and submarines at a high data transfer rate (Qinetiq, 2009). The SEADEEP system consists of a blue/green laser “transceiver” module (both transmitter and receiver) providing two-way network connectivity between a submarine and aircraft, most likely an UAV. Additional research is being conducted in underwater acoustics that use lasers as the sound source. The laser ionizes a small amount of water that generates a sound pulse. Research related to environmental and biological impacts of sound is a rapidly growing area of study. Assessing potential environmental impacts related to underwater sound is outside the scope of this report.

3.3 BIOFOULING PREVENTION USING ULTRAVIOLET RADIATION.

There is an increasing trend in the use of optical sensors deployed in the marine environment for long-term monitoring of various physical and chemical oceanographic parameters (Prien, 2007; Moore et al., 2008). Examples of these instruments include optical scattering sensors (turbidity sensors), chlorophyll fluorometers, photosynthetically active radiation (PAR) sensors, spectral radiometers (radiance and irradiance), spectral backscattering, spectral absorption, and spectral beam attenuation meters. These sensors serve a growing capacity in modern environmental monitoring and play a key role in understanding small-scale spatial and temporal dynamics of oceanographic processes which are important to operational readiness. Biofouling of the lens on these optical systems degrades functionality and is a limiting factor for longevity of deployment (Strahle, Hotchkiss, and Martini, 1998). Biofouling is initiated by bacteria and unicellular algae that forms a biofilm or slime layer (Callow and Callow, 2002). Disruption of biofilm formation inhibits further colonization from other organisms. Various mechanical and chemical methods have been used to help keep the lens clean. Mechanical methods include diver-led manual cleaning and windshield wiper style systems (Manov, Chang, and Dickey, 2004). Chemical methods include copper, zinc, and other organic antifouling coatings or matrices, while submarines have used a formalin bath for periscopes (Strahle, Perez, and Martini, 1994; Manov, Chang, and Dickey, 2004). Using ultraviolet (UV) light to control microbial growth is well established with recent efforts to use UV to prevent biofouling on optical systems (Bank, John, Schmehl, and Dratch, 2009). While technically not a laser, this technology has been included in this report because of its emerging research and development efforts.

3.4 NAVY WIDE USAGE

The various applications and systems mentioned above are all used in some capacity at Navy ranges or laboratories. LiDAR is the most prominent laser system currently used by the Navy in the marine environment. Near-shore coastal mapping around Navy facilities using LiDAR is becoming a powerful tool used by facilities and natural resource planners to provide key baseline information for assessing the potential impacts of climate change and sea-level rise. LiDAR used in mine detection training and operations also continue to be an important part of the Navy's mine countermeasure tools. A review of recent range and warfare center EISs shows the extent to which LiDAR is used by ALMDS and LLS (Table 2).

Table 2. LiDAR system usage at various Navy facilities.

Location/Training Range	LiDAR System	
	ALMDS	LLS
Navy Cherry Point Range Complex[1]	X	X
Virginia Capes Range Complex[2]	X	----
Naval Surface Warfare Center Panama City Division[3]	X	X
Gulf of Mexico Range Complex[4]	X	----
Jacksonville Range Complex[5]	X	X
Keyport Range Complex[6]	X	----
Point Mugu Sea Range[7]	----	----
Northwest Training Range Complex[8]	----	----
Silver Strand Training Complex[9]	X	----
Southern California Anti-Submarine Warfare Range Complex[10]	----	----
Southern California Range Complex[11]	X	----
Hawaii Range Complex[12]	X	----
Marianas Range Complex[13]	----	----

1. DoN 2009a 4. DoN 2008c 7. DoN 2002 10. DoN 2006a 13. DoN 2009e
2. DoN 2009b 5. DoN 2009c 8. DoN 2008e 11. DoN 2008b
3. DoN 2008a 6. DoN 2008d 9. DoN 2009d 12. DoN 2008f

4. RESULTS

4.1 BIOLOGICAL SYSTEMS

The laser systems used within the marine environment have a potential for exposure to the organisms found living there. The exposure route and potential effects vary depending on the laser systems used and the type of organism exposed. To determine the potential impact of a laser system to an organism in the marine environment, an assessment pathway with the following four components was developed.

1. **Laser System Specifications.** Laser systems that may result in exposure to a particular organism are identified, and a representative laser system is selected for impact assessment. System specifications include power, wavelength, frequency, pulse width, and spot size or divergence.
2. **Exposure Potential.** This variable addresses the potential for an organism to come in contact with a laser and the mechanism or route in which exposure could occur. This variable may be defined by geographic location, temporal trends/behavior, location or depth in the water column, and exposure routes (e.g., eye or body).
3. **Damage Thresholds.** This variable addresses potential effects to an organism if exposure was to occur. This variable may be defined by species-specific physiological characteristics or traits.
4. **Potential Impacts.** Based on the information outlined in the above three variables, estimates on potential impacts from laser systems to marine organisms can be determined.

The sections below outline the major groups of organisms which may be exposed to laser systems. Laser systems are identified that may result in exposure for each biological group, and the most environmentally conservative exposure potential and system parameters are chosen to explore impacts. This approach provides a worst case scenario to ensure the full breadth of potential exposure is incorporated. Before assessing potential impacts of laser systems to marine organisms, information on how light behaves in the marine environment first needs to be addressed.

4.2 LIGHT IN THE MARINE ENVIRONMENT

The behavior of laser light when it enters the water and within the water column involves a complex set of interactions. This behavior is difficult to accurately model, and remains to be studied at great length. A laser beam's behavior, as it pertains to airborne laser systems, can be separated into two basic elements, energy transfer at the air–water boundary and light propagation through the water column.

The amount of laser energy that enters the water from an airborne source is a function of the laser beam behavior at the air–sea interface and is dependent on several variables. In addition to system parameters (e.g., wavelength, and power) these variables include laser scanner angle, sun angle, and sea state or water surface texture. The amount of energy that is reflected or absorbed depends on the angle of the source energy and water surface condition, and varies for different wave types, e.g., small, wind-driven capillary waves or larger, more developed gravity waves (Guenther, 1986; Mobley, 1994). To provide the most conservative (worst case) values, the following parameters are assumed: the laser scanner angle is 90°, the sun is at its zenith (directly overhead), and the water's surface is completely flat. Therefore, all of the energy from the airborne laser system at the water's surface will transfer into the water column and is the starting value for assessing attenuation.

To assess any impacts from laser energy to marine organisms below the water's surface, it is important to know what the energy exposure is at a particular depth. This is dictated by the light/energy attenuation, or extinction through the water column. The Lambert-Beer's Law is used to estimate laser energy, relative to the surface, at a given depth by the following:

$$I_z = I_o e^{-kz}, \qquad \text{(Equation 1)}$$

where I_z is the energy value at depth z, I_o is the energy value at the water surface, k is the extinction coefficient, and z is the depth. Different extinction coefficients can be used in this equation, including beam attenuation coefficient, diffuse attenuation coefficient, as well as a system-specific LiDAR attenuation coefficient.

Beam attenuation is a combination of spectral absorption and spectral scattering as it relates to radiant energy, and can be represented mathematically by $c(\lambda) = a(\lambda) + b(\lambda)$, where $c(\lambda)$ is the total beam attenuation coefficient for a specific wavelength (λ) and $a(\lambda)$ and $b(\lambda)$ are the absorption and scattering coefficients, respectively, for that wavelength (Mobley, 1994). Absorption is the amount of energy absorbed by the water itself, as well as other biologic and inorganic particles. Light absorption by the water itself has been closely studied in both pure and saltwater at various wavelengths and is considered a constant (Clarke and James, 1939; Baker and Smith, 1982). Scattering is the interaction between light and various organic and inorganic particles, and is more difficult to measure and model.

The diffuse attenuation coefficient relates to incident lighting and is commonly evaluated in terms of downwelling irradiance (Mobley, 1994; Zheng, Dickey, and Chang, 2000). Smith and Baker and Smith (1982) present a bio-optical model outlining three major components that influence overall absorption which is summarized by $K_T(\lambda) = K_W(\lambda) + K_C(\lambda) + K_D(\lambda)$, where $K_T(\lambda)$ is total absorption, $K_W(\lambda)$ is the component due to water itself, $K_C(\lambda)$ is the chlorophyll component, and $K_D(\lambda)$ is the component due to dissolved organic matter (DOM). The major difference between the beam attenuation coefficient and diffuse attenuation coefficient is that beam attenuation is the radiant power lost from a narrow collimated beam with depth, whereas diffuse attenuation deals with a decrease in irradiance of a diffuse or uncollimated light field (Mobley, 1994).

Figure 4 shows the energy decay, with a starting surface value based on the SHOALS-3000 (Table 1) for various extinction coefficients (Note: for this comparison all extinction coefficients are represented by the variable "k", while in the literature, various attenuation coefficients, e.g., beam and diffuse, have different/unique nomenclature).

The four curves represent varying degrees of light (energy) penetration, from a theoretical maximum to extremely high attenuation in turbid coastal waters.

The first curve (dark blue) represents pure water with an extinction coefficient of k = 0.035, where no particulate or dissolved matter is in the water. This extinction coefficient will never be found in a real-world/marine setting, but serves as a bounding curve illustrating the maximum beam penetration.

The second curve (green) represents the diffuse attenuation due to absorption by seawater at a wavelength of 532 nm and has a value of k = 0.053 (Baker and Smith, 1982). The green curve represents the maximum penetration achievable in seawater and is based on K_W (λ = 532), or absorption due to seawater at 532 nm, excluding absorption by chlorophyll [$K_C(\lambda)$] and DOM [$K_D(\lambda)$] , as well as any particulate scattering.

The third curve (red) represents empirically measured LiDAR attenuation coefficient(s) from a cruise in the Southern California Bight, with a mean value of k = 0.098 (Churnside, Tatarskii, and Wilson, 1998).

Although the study was limited to only a few water types (see Mobley, 1994 for explanation of Jerlov water types), the LiDAR attenuation coefficient provides a good representation of how the energy will decay through the water column and is used in later sections to estimate exposure potential at various depths, while beam attenuation and diffuse attenuation are the optical properties of seawater.

The fourth curve, light blue, represents the energy decay in turbid or “dirty” water with a diffuse attenuation coefficient of k = 0.400 (Guenther, Eisler, Riley, and Perez, 1996). This curve represents the opposite extreme from the pure water coefficient and serves as a bounding curve for rapid attenuation.

Depending on which attenuation curve is used, potential laser exposure at a given depth varies widely. For example, at a depth of 10 m, the amount of energy remaining from the initial surface value is 70, 59, 37 and 2% for the different curves (Figure 4). This study is interested in the amount of energy in terms of irradiance exposure (J cm^{-2}) to marine organisms, and uses the irradiance value from the SHOALS-3000 (Table 1) as a starting surface value and the LiDAR attenuation coefficient to estimate energy decay through the water column, and thus, exposure at depth.

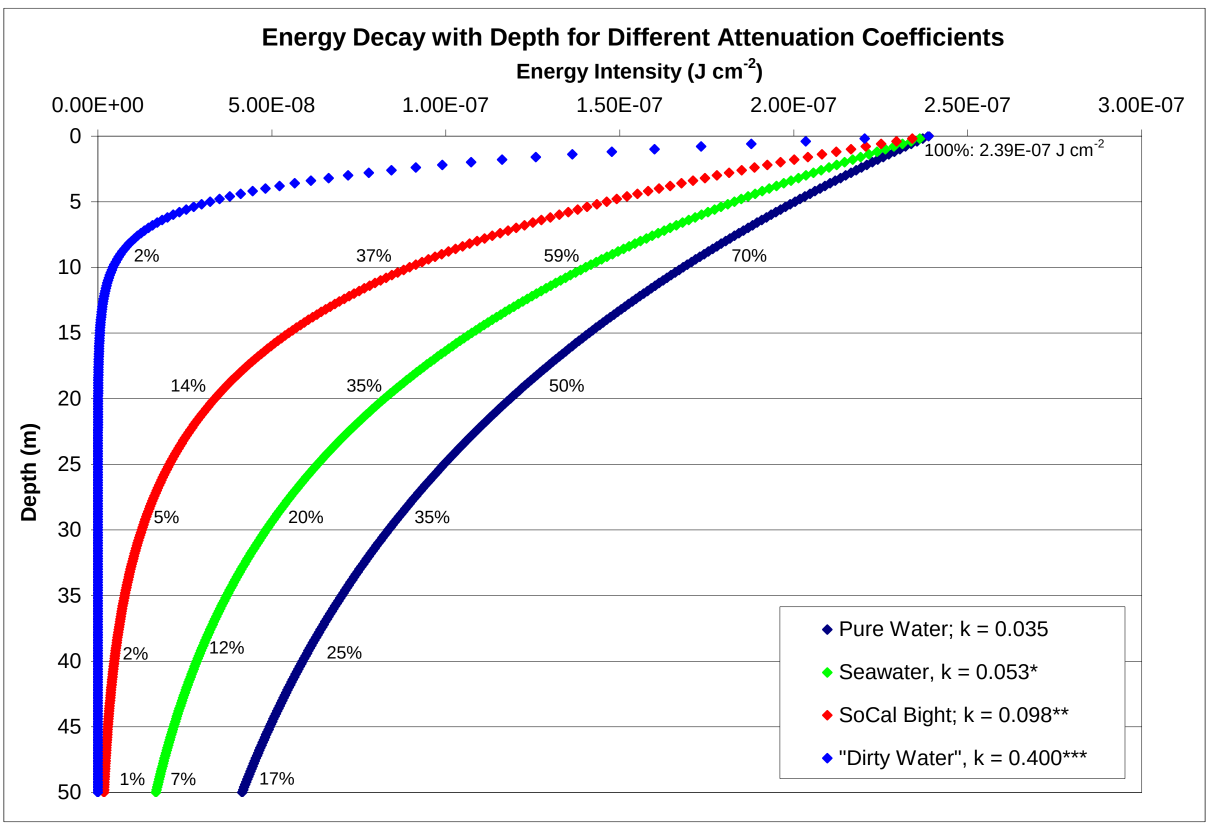

Figure 4. Energy decay of a LiDAR system (Table 1) with different extinction coefficients (Equation 1). The percentages next to the curve represent the energy remaining from the starting surface level. * Baker and Smith, 1982; ** Churnside, Tatarskii, and Wilson, 1998; *** Guenther, Eisler, Riley, and Perez, 1996.

4.3 MARINE MAMMALS, FISH, AND REPTILES

To determine the potential impact of laser systems to marine mammals, fish, and reptiles the assessment pathway outlined in section 5.1 was followed. The most environmentally conservative system, and system parameters, are chosen to explore impacts. This approach provides a worst case scenario to ensure the full breadth of potential exposure is incorporated.

4.3.1 Laser System Specifications

LiDAR has the greatest energy per area (joules cm^{-2}) of the various laser systems assessed in this report. The SHOALS-3000 will be used as the representative LiDAR system for assessing potential impact, with output parameters defined in Table 1.

4.3.2 Exposure Potential

Mammals, fish, and sea turtles have a variety of exposure routes from laser systems used in the marine environment. Laser exposure occurs to the organism's eyes and/or body/skin surface. The potential for hazardous exposure is greater above the water's surface than below due to the rapid attenuation of laser energy in the water column (Figure 4). Additionally, the laser energy required to cause damage to eyes is far less than to other body areas (ANSI, 2007). To best assess potential impacts of lasers to this group of organisms, the most conservative exposure scenario and route will be used as a starting point. Therefore, the greatest chance of injury would be to the ocular systems of marine mammals and sea turtles from LiDAR exposure above the water's surface. This scenario represents the worst case for laser exposure, but is considered an extremely rare event. The likelihood of exposure is a very rare event based on the number of annual training hours during which these laser systems are used and marine mammal/sea turtle densities outlined in various range EIS reports (e.g., DoN 2008a,b,c; 2009a,b). To receive direct ocular exposure, the animal would have to be in the geographical area of the training exercise and would need to surface and be looking up at the same time a LiDAR system fly's overhead.

4.3.3 Damage Thresholds

Vision and hearing sensory systems in marine mammals and sea turtles play an important role in feeding, socializing, predation avoidance, and reproduction (Mobley and Helweg, 1990, Lutz, Musick, and Wyneken, 2003). Compared to terrestrial mammals, the vision systems of marine mammals and sea turtles have specific features allowing them to function in water and air. These features also are important for the ability to function under the more extreme conditions in the marine environment such as low temperatures, increased pressure at depth, and high amounts of suspended particles (Mass and Supin, 2002). Certain morphological features of the eye differ among various marine mammal groups (e.g., cetaceans, pinnipeds, sirenians, sea otters), although mechanisms exist to allow all the groups to achieve emmetropia both in and out of water (Mass and Supin, 2002). One of the biggest differences between terrestrial and marine organism's vision systems is related to how light is refracted through the eye and focused on the retina. The cornea is the main refractive element in terrestrial mammals. However, for marine organisms, because water and corneal tissue have similar refractive indices (1.33 to 1.35), the cornea is unable to provide any refractive power. The primary refracting element for marine mammals and sea turtles is the lens, which is spherical in most cases (Fernald, 1990; Mass and Supin, 2002), while the pupil adjusts for how much light passes through to the retina.

The wavelength and pulse width of a laser determines the mechanism of ocular damage. Based on the LiDAR system parameters explored in this report, the primary mechanism of damage to the eye would be thermal damage to the retina (Zorn, Churnside, and Oliver, 2000). The amount of light, and therefore, potential laser exposure to the retina is dependent on the pupil diameter and the focusing ability, or retinal resolution, of the eye.

Visual acuity is a measure of the resolving power of the eye, or the ability to distinguish two objects from each other, and in healthy/normal eyes is a proxy of retinal resolution. Visual acuity can be measured or estimated in several ways. The first method estimates retinal resolution from ganglion cell density (Mass and Supin 2000, 2003, 2005). Retinal resolution is defined as the mean angular distance between adjacent ganglion cells. A topographic distribution of ganglion cell density (cells mm^{-2}) from the retina is generated, and the areas of highest density are used as an estimate of the best possible resolving power. Angular retinal resolution is calculated using ganglion cell density and the posterior nodal distance (PND), also referred to focal length, using the following formula:

$$\alpha = 180° / \pi \, r \, \sqrt{D} \, , \qquad \text{(Equation 2)}$$

where α = inter-cell angular distance, r = PND, and D = ganglion cell density (cells mm^{-2}). The angular retinal resolution is often converted to minutes of arc, i.e., $\alpha = 0.20°$ or 12' of arc. Additionally, resolvable spatial frequency is a common metric of retinal resolution calculated from the inter-cell angular distance using the following formula: $f = 1/2\alpha$. The visual acuity of 0.20° (12') corresponds to a spatial frequency of 2.5 cycles/degree. The second method for estimating visual acuity involves the behavioral response of the animal tested to visual stimuli. This method has been used on various marine mammals (e.g., Herman, Peacock, Yunker, and Madsen, 1975; Bauer et al., 1999) and corresponds well with acuity based on ganglion cell measurements (Mass and Supin, 1995; Mass, Odell, Ketten, and Suppin, 1997). Additionally, the visual acuity of sea turtles has been estimated using electrophysiological methods (Bartol, Musick, and Ochs, 2002).

The visual acuity and pupil diameter of marine mammals and sea turtles are species specific. Therefore, for any given laser exposure the energy at the retina (potential for damage) will vary among species. Additionally, measured laser safety thresholds for marine mammals or sea turtles do not exist. Zorn, Churnside, and Oliver (2000) present a way to estimate the laser safety thresholds for cetaceans and pinnipeds. The authors present a method of normalizing species-specific exposure to the retina, and then compare the results to published safety thresholds for humans. The American National Standards Institute (ANSI) publishes laser safety limits for various wavelengths and exposure times termed Maximum Permissible Exposure (MPE). The ANSI (2007) MPE for human ocular injury from the LiDAR systems is 5×10^{-7} J cm^{-2} (with a 400- to 700-nm wavelength and an exposure time of 10^{-9} to 1.8×10^{-8}). Zorn, Churnside, and Oliver (2000) estimate the energy density at the retina for individual species based the following formula:

$$E_r = \frac{E_c d_e^2}{f_e^2 \rho^2} , \qquad \text{(Equation 3)}$$

where E_r is the energy at the retina, E_c is energy at the cornea, d_e is the pupil diameter, f_e is the PND or focal length, and ρ is the visual acuity in minutes of arc. Table 3 lists the human E_r value using the MPE noted above and various ocular measurements (Zorn, Churnside, and Oliver, 2000).

Table 3. Input parameters for the calculation of E_r for humans.

Ec (J/cm^2)	Pupil Diameter (mm)	Focal Length (mm)	Visual Acuity (min of arc)	Er (J/cm^2)
5.00E-07	**7**	**17**	**1**	**8.48E-08**

Zorn, Churnside, and Oliver (2000) calculated a sensitivity ratio for various marine mammals using the initial MPE with species-specific ocular dimensions and visual acuity. The sensitivity ratio is calculated using the following formula:

$$\gamma = \frac{E_{rs}}{E_{rh}}, \qquad \text{(Equation 4)}$$

where E_{rs} is the energy density on the retina of a particular species, and E_{rh} is the energy density on the retina of a human. Finally, an estimate for the maximum exposure limits for marine mammals is given by dividing the human MPE value by the sensitivity ratio for that species. Zorn, Churnside, and Oliver (2000) calculated sensitivity ratios for 11 species of cetaceans and pinnipeds. Calculated sensitivity ratios and single exposure limits, updated ocular dimensions, and additional marine mammal species (including manatees, sea otters, and sea turtles) are presented in Table 4, which includes a summary of information presented in Zorn, Churnside, and Oliver (2000).

4.3.4 Potential Impacts

Using the laser parameters of the SHOALS system (Table 1) as a baseline for comparison, the potential exposure from LiDAR systems is less than half the Human MPE value ($5x10^{-7}$ J cm^{-2}). The Fur Seal (*Callorhinus ursinus*) has the highest sensitivity ratio of the species assessed in this study (0.167), resulting in a single exposure limit of 2.99×10^{-6}. The supplemental ocular morphological information and additional species looked at in this study support the findings from Zorn, Churnside, and Oliver (2000), that LiDAR systems designed to meet the human MPE value will be safe to any marine mammal or sea turtle that may be exposed. Additionally, based on the calculated single exposure limits in Table 4, these animals could withstand laser exposures from more powerful systems. This exposure scenario also is representative of a worst case, whereas the actual chance of exposure is low. Based on the number of annual training hours these laser systems are used and marine mammal/sea turtle densities outlined in various range EIS reports (e.g., DoN 2008a,b,c; 2009a,b) and the rare likelihood of an animal surfacing and receiving subsequent eye exposure. Based on the identified system parameters, exposure potential, and damage thresholds for marine mammals and sea turtles to the laser systems currently in use pose no environmental risk.

4.4 PLANKTON

Plankton have limited locomotive abilities and their movements are mostly dictated by prevailing circulation patterns (Nybakken, 2004). Plankton can be divided into two major categories, phytoplankton and zooplankton. Phytoplankton are microscopic unicellular algae capable of photosynthesis, while zooplankton refers to free-floating animals. Zooplankton are a trophic level above phytoplankton, which they often feed or graze on. Within the zooplankton community, organisms with different life cycles exist; holoplankton spend their entire life in the plankton, while meroplankton spend only a portion of their lives as plankton and include juvenile stages or larvae of fish and crustacean species (Nybakken, 2004).

Table 4. Calculated Sensitivity Ratios (SR) and Single Exposure Limits (SEL) for various marine mammals and sea turtles. SR and SEL values were conservatively based on the highest E_r value for each respective species.

Common Name	Species	Lens Diameter (mm)	Pupil Diameter (mm)	Focal Length (mm)	Visual Acuity (min of arc)	Er (J cm^{-2})	Sensitivity Ratio (γ) (max)	Single Exposure Limit (J cm^{-2})
Gray Whale	Eschrichtius robustus	11.8 [21]		23 [14, 21]	11 - 14 [14, 21]	6.71E-10 - 1.09E-09	0.013	3.90E-05
Minke Whale	*Balaenoptera acutorostrata*	20.5 [35]		40 [29]	7.1 - 7.6 [29]	2.28E-09 - 2.61E-09	0.031	1.62E-05
Beluga Whale	Delphinapterus leucas	7.5 - 7.7 [16, 28]		12 - 13.5 [16, 28]	11.8 - 16.9 [16, 28]	6.84E-10 - 1.17E-09	0.014	3.63E-05
False Killer Whale	*Pseudorca crassidens*	10.5 [28]		17 [28]	9.3 [28]	2.21E-09	0.026	1.92E-05
Atlantic Bottlenose Dolphin	*Tursiops truncatus*		10 [4]	14.5 - 16 [5, 13, 20]	8 - 14 [9, 13, 20, 31]	1.21E-09 - 3.72E-09	0.044	1.14E-05
Common Dolphin	*Delphinus delphis*	10 [35]		16 [6]	8 - 9.5 [6]	2.16E-9 - 3.05 E-9	0.036	1.39E-05
Harbor Porpoise	*Phocoena phocoena*	9 [11]	8 [11]	11.5 [20, 25]	11 - 14 [25]	1.23E-9 - 2.00E-9	0.024	2.12E-05
Dall's Porpoise	*Phocoenoides dalli*	9 [35]		12.5 [27, 29]	11.5 - 12.2 [27, 29]	1.74E-9 - 1.96E-9	0.023	2.16E-05
Pacific white-sided dolphin	*Lagenorhynchus obliquidens*	9.1 [28]		13 [28]	11.2 [28]	1.95E-09	0.023	2.17E-05
Steller Sea Lion	*Eumetopias jubatus*	13 [24]	7.5* [24]	19 [18, 24]	4.15 [18, 24]	4.52E-09	0.053	9.37E-06
Fur Seal	*Callorhinus ursinus*	15.9 [19]		22.5 [19]	4.2 [19]	1.42E-08	0.167	2.99E-06
California Sea Lion	*Zalophus californianus*	14.4 [34]	16.7 [12]	22.8 [35]	5 - 9 [34]	3.31E-09 - 1.07E-08	0.127	3.95E-06
Harbor Seal	*Phoca vitulina*	16.7 [10]	10.5 - 14.5 [7, 12]	22 [10]	8.1 - 8.6 [33]	1.54E-09 - 3.31E-09	0.039	1.28E-05
Harp Seal	*Pagophilus groenlandicus*	16 [17]	6.2* [23]	26 [17, 23]	2.7 - 3.3 [17]	2.61E-09 - 3.90E-09	0.046	1.09E-05
WI Manatee	*Trichechus manatus*		5* [8]	11* [X]	20 - 66 [2, 15]	2.37E-11 - 2.58E-10	0.003	1.64E-04
Sea Otter	*Enhydra lutris*		2.1 [22]	7 [22]	7 [22]	9.18E-10	0.011	4.62E-05
Loggerhead Sea Turtle	*Caretta caretta*	5.2***		14.4***	5.34 [1]	2.29E-09	0.027	1.85E-05
Leatherback Sea Turtle	*Dermochelys coriacea*	8.2 [3]	4.3 [3]	18.7 [3]	1.9** [30]	7.32E-09	0.086	5.79E-06
Green Sea Turtle	*Chelonia mydas*	5.2 [26]		14.4 [26]	2.2** [30]	1.35E-08	0.159	3.15E-06

1. Bartol et al., 2002
2. Bauer et al., 2003
3. Brudenall et al., 2008
4. Dawson, 1980
5. Dral, 1977
6. Dral, 1983
7. Hanke et al., 2006
8. Harper, 2004
9. Herman et al., 1975
10. Jamieson and Fisher, 1972
11. Kroger and Kirschfeld, 1994
12. Levenson and Schusterman, 1997
13. Mass, 1993
14. Mass, 1996
15. Mass et al., 1997
16. Mass, 2001
17. Mass, 2003
18. Mass, 2004
19. Mass and Supin, 1992
20. Mass and Supin, 1995
21. Mass and Supin, 1997
22. Mass and Supin, 2000
23. Mass and Supin, 2003
24. Mass and Supin, 2005
25. Mass et al., 1986
26. Mathger et al., 2007
27. Murayama, 1995
28. Murayama and Somiya, 1998
29. Murayama et al., 1992
30. Oliver et al., 2000
31. Pepper and Simmons, 1973
32. Schusterman, 1972
33. Schusterman and Balliert, 1970
34. West et al., 1991
35. Zorn, 2000

3 * Estimated from diagram

** Calculated from ganglion cell density

*** Estimate based on *Chelonia mydas*

Light is critical to phytoplankton survival since they rely on photosynthesis as a means of food/energy production. Photosynthesis takes place when PAR is absorbed by the phytoplankton. PAR falls between 400 and 700 nm on the electromagnetic spectrum. Chlorophyll-a is the primary pigment used in photosynthesis. Different supplementary pigments exist, such as carotenoids and phycobilins, as well as other forms of chlorophyll that aid in photosynthesis (Nicklisch, 1998; Culver and Perry, 1999). The light-absorbing systems of phytoplankton make them more susceptible to damage from lasers than other planktonic forms, and are used as the conservative end-point measurement associated with potential laser exposure.

4.4.1 Laser System Specification

Two of the laser systems identified in this report may result in exposure to phytoplankton, one above surface and one subsurface. Of the systems using wavelengths in the blue-green spectrum, LiDAR presents the greatest potential for damage in terms of energy per unit area, and the SHOALS-3000 LiDAR system will be used as a representative laser source (Table 1). The subsurface laser source is the UV light biofouling prevention system.

4.4.2 Exposure Potential

LiDAR

Exposure potential from LiDAR systems is directly related to the depth in the water column where phytoplankton are found. The laser energy attenuates rapidly with depth, and thus the higher in the water column, the greater the laser intensity (Figure 4). The relative position in the water column of the plankton, therefore, is an important element in defining exposure. The location in the water column of phytoplankton is dependent on a host of variables, including the water's density, depth of the euphotic zone, and nutrient availability. A combination of these variables leads to optimal conditions for growth at some depth. Under certain hydrographic conditions, phytoplankton exhibit a mid-depth maximum where the highest densities are observed at some depth below the surface (Estrada et al., 1993). This chlorophyll maximum can vary, but is often between 20 and 60 m (Perez et al., 2006; Uitz, Claustre, Morel, and Hooker, 2006). Overall, phytoplankton are mixed throughout the water column and the densities at the immediate surface represent only a fraction of the entire community for that given area. Additionally, phytoplankton have a high degree of temporal variability with the highest densities found during the spring and fall, respectively, associated with hydrographically driven nutrient enrichment (Cloern and Nichols, 1985). Because phytoplankton are found in various densities throughout the water column, populations vary widely throughout the year and over different geographic areas, and laser energy attenuates rapidly with depth, the exposure potential from LiDAR to the phytoplankton community as a whole is generally low.

UV LED Biofouling Prevention System

The UV systems aimed at controlling biofouling on optical systems still is in a research and development phase and currently is not widely used in any training or system applications[14] (Kurtz, 2009). As such, system parameters are not well defined and establishing a baseline or representative exposure will be difficult. However, the basic system design is based on low-powered UV LEDs used to clean small optical windows (~2- to 5-cm diameter). Any potential exposure would only occur on a very small scale, and dissipate quickly through the water column. Additionally, the fluid

[14] Personal communication with Cheryl-Anne Kurtz at SSC Pacific using UV LED to prevent biofouling of optical windows. Contact author for information.

nature of the phytoplankton and the light duty cycles of the system would most likely result in only a single exposure.

4.4.3 Damage Thresholds

LiDAR

The photoreceptor cells of phytoplankton are sensitive, and high light levels may cause photoinhibition, a decline in photosynthesis, especially in the upper water column (Lewis and Smith, 1983; Eilers and Peters, 1988; Rehak, Celikovsky, and Papacek, 2008). However, photoinhibition may be due to a saturation of photoreceptor cells, which phytoplankton may acclimate to over time, or temporary damage rather than any lasting cellular damage (Han, 2002; Ross, Moore, Suggett, MacIntyre, and Geider, 2008). Laser energy may cause lethal damage by structural destruction or intracellular damage. A paucity of data exists on specific laser survival or damage thresholds of phytoplankton. Rather, most studies assessing lasers impact on phytoplankton have been aimed at a lethal end-point, with the goal of controlling phytoplankton growth. Nandakumar et al. (2002, 2003a,b, 2009) have investigated the impacts of lasers on various plankton species, two diatoms (*Skelotonema costatum*, *Chaetoceros gracilis*), a dinoflagellate (*Heterocapsa circularisquama*), and the planktonic stage of a barnacle (*Balanus amphitrite*).

The general parameters of the laser system(s) used in these experiments were similar to a LiDAR system, a Nd:YAG laser with a wavelength of 532 nm, a pulse width of 5 ns, and a frequency of 10 Hz. The experimental design had laser fluences that varied from 0.025 to 0.1 J cm^{-2} and exposure times that varied from 2 to 300 seconds. Mortality was experienced even at the lower laser fluence and exposure times, although there were species-specific differences. Under the lowest laser fluence (0.025 J cm^{-2}) and shortest exposure time (3.57 seconds), the mortality for *S. costatum* and *C. gracilis* was 66 and 23%, respectively (Nandakumar et al., 2003a).

A different experiment showed mortality for *S. costatum* and *C. gracilis* with a laser fluence of 0.1 J cm^{-2} and exposure of 2 seconds to be 46 and 52%, respectively (Nandakumar et al., 2003b). The laser fluence from these experiments is much higher than what would be experienced from a LiDAR system, and also represents multiple exposures. Table 4 shows the total laser dose values for two different laser fluences and exposure times from the experiments by Nandakumar et al. (2003a,b) compared to the SHOALS 3000 LiDAR system. A laser fluence of 0.025 J cm^{-2} at a frequency of 10 Hz (cycles per second) yields multiple exposures during 3.57 seconds, resulting in a total exposure or dose of 0.9 J cm^{-2}. Laser exposure to phytoplankton from a LiDAR system would result in a single exposure from a laser fluence several orders of magnitude lower than that of the experimental system used by Nandakumar et al. The total laser exposure (or dose) from a LiDAR system would be 2.39 x 10^{-7} J cm^{-2}, or 3.8 million times less powerful than the lowest laser dose used in the experiments (Table 5).

Table 5. Laser dose values based on different laser fluences and exposures from Nandakumar 2003a compared to the SHOALS 3000 LiDAR.

Laser System or Experimental Design	Laser Fluence (J cm^{-2})	Number of Exposures	Total Laser Energy (J cm^{-2})
Low Exposure (~40% Mortality)	2.50E-02	36	9.00E-01
Moderate Exposure (~80% Mortality)	1.00E-01	109	1.09E+01
SHOALS 3000	2.39E-07	1	2.39E-07

UV Biofouling Prevention System

Ultraviolet light (UVA: 400 to 320 nm; UVB: 320 to 290 nm) initiated impacts to phytoplankton, as related to cellular damage and photoinhibition, has been well documented (e.g., Cullen, Neale, and Lesser, 1992; Xenopoulos, Frost, and Elser, 2002; Villafane, Buma, Boelen, and Helbling 2004; Helbing, Buma, vdPoll, Zenoff, and Villafane, 2008; Villafane, Janknegt, de Graaff, Visser, van de Poll, Buma, and Helbling, 2008). However, this damage is from long term UV exposure from the sun rather than a small intermittent light pulse. No available data exist related to plankton damage from UV light at the levels generated from the biofouling prevention system.

4.4.4 Potential Impacts

LIDAR

The potential for damage to phytoplankton, and thus, other planktonic forms, from LiDAR systems is improbable. There is a small chance that phytoplankton actually will be exposed to LiDAR energy, and in the event that exposure does take place, the energy levels are unlikely to cause any damage. Although the lowest laser dose from experiments by Nandakumar et al. (2003a,b) resulted in phytoplankton mortality, the LiDARs energy is six orders of magnitude lower and any possibility of damage decreases dramatically with depth. Additionally, the distribution of phytoplankton in the water column is such that near surface densities represent only a small proportion of the entire community at any given location. Due to the dynamic nature and high temporal and spatial variability of plankton, the low fluence values of the systems, and the limited chance for exposure LiDAR poses no significant risk to overall planktonic communities. These conclusions are based on best available data in literature, although no specific thresholds are reported.

UV LED Biofouling Prevention System

The UV biofouling prevention system also does not pose a risk to the planktonic community. The exposure potential to the planktonic community is extremely low. The system is expected to be deployed only in small numbers, in addition to a very confined area of potential impact (based on optical window size and UV attenuation). A paucity of data exists related to plankton specific damage from UV at the levels generated by the system.

4.5 BENTHIC COMMUNITIES

Benthic communities encompass a wide range of organisms that are found living in, or in association with, the seafloor. Of importance are those organisms that are sessile or have limited locomotive capabilities. The biological end-points are separated into two categories, benthic invertebrates and coral reefs. Benthic invertebrates include a diverse assemblage of organisms including polychaetes, crustaceans, echinoderms, and mollusks. Coral reef ecosystems are an important natural resource and unique in that they have a symbiotic relationship with zooxanthellae, a photosynthetic algae (Nybakken, 2004). Zooxanthellae play a critical role in providing an energy source to the corals and, as is the case with phytoplankton, are subject to damage or photoinhibition from extreme light conditions (Bhagooli and Hidaka, 2004). Damage to the zooxanthellae can prove deleterious to the coral and may result in a phenomenon termed bleaching where the zooxanthellae are expelled from the coral, which may ultimately result in coral death (Nybakken, 2004).

4.5.1 Laser Systems

The laser systems that may affect benthic organisms are LiDAR and LLS, in the blue/green wavelengths, as well as the UV LED biofouling prevention system.

4.5.2 Exposure Potential

LIDAR and LLS

Potential exposure from LiDAR systems to benthic organisms is low based on rapid attenuation through the water column (Figure 4). In the case of LLS, the exposure potential may be higher because the systems are deployed subsurface in closer proximity to the benthic organisms. Even with the system being closer to the benthic organisms, LLS systems are typically deployed between 3 and 9 meters above the seafloor, for which energy intensities would decrease to 74 and 41% of initial output, respectively (NOAA, 2001; Figure 4).

Unlike phytoplankton, corals are sessile and may be found in greater abundance higher in the water column, although overall laser exposure potential is low based on training locations and training duration. Exposure potential would be more likely during bathymetric mapping than range training exercises, and if exposure did occur, it would be limited to a one-time single exposure.

UV LED Biofouling Prevention System

Potential exposure from the UV LEDs is limited to corals and not other benthic invertebrates. The UV system aimed at controlling biofouling on optical windows still is in a research and development phase, and currently is not widely used in any training or system applications (Kurtz, 2009). As such, system parameters are not well defined, and establishing a baseline or representative exposure will be difficult. However, the basic system design is based on low-powered UV LEDs used to clean small optical windows (~2- to 5-cm diameter). The research and development efforts to incorporate UV LEDs to prevent biofouling as part of the Automated Health Assessment of Coral Reefs project (SSC Pacific) would result in a more chronic long-term exposure versus that of the LiDAR systems previously discussed.

The monitoring system faces the coral at a fixed distance (6 to 12 inches) and measures the fluorescence over time to assess coral health. The system is designed to be deployed for long-term assessment on the order of 6 months to a year or longer. The UV LED would be incorporated in the housing of this instrument to keep the optical window clean, and thus, also faces the coral. The diffuse attenuation of UV in water is greater than that of the LiDAR systems (532 nm), so the energy would dissipate more rapidly from the source. The diffuse attenuation values for UV vary widely by location due to water clarity differences (Tedetti and Sempere, 2006). In very clear oligotrophic blue waters, observed K_d values range from 0.1 to 0.3 m^{-1} and approximately 0.07 m^{-1} for 305 nm and 380 nm wavelengths, respectively (Hargreave, 2003; Zepp, Shank, Stabenau, Patterson, Cyterski, Fisher, Bartels, and Anderson, 2008). Attenuation values for waters will moderate clarity range from 0.4 to 0.9 m^{-1} for the 305-/310-nm wavelength and 0.17 to 0.28 m^{-1} for 380 nm (Dunne and Brown, 1996; Zepp et al., 2008). For more turbid waters, K_d values of 1.5 m^{-1} and 0.76 m^{-1} were observed for 320 nm and 380 nm, respectively (Dunne and Brown, 1996).

4.5.3 Damage Thresholds

LIDAR

There are no known available data associated with laser energy impacts on benthic invertebrates or corals. Most benthic organisms have a hard protective outer layer or shell to which even modest laser energy would unlikely have any impacts. Crustaceans have developed eyes that may be adapted for a wide range of light environments (Cronin and Jinks, 2001). Most of the work done on assessing retinal damage in crustaceans has been related to deep-sea organisms, or those acclimated to very low light conditions. Organisms that were adapted to low-light environments were exposed to illuminance levels approximating daylight for various lengths of time, varying from minutes to hours (e.g., daylight exposure for 10 minutes resulting in 4.2×10^6 J m^{-2}) and retinal damage was assessed

(Nilsson and Lindstrom, 1983; Shelton, Gaten, and Chapman, 1985). Data on the effects of laser energy to corals also are lacking, although it can be assumed that damage thresholds would be similar to phytoplankton based on the photosynthetic activity of the zooxanthellae.

UV Biofouling Prevention System

The effect of UV light from solar radiation on corals has been well studied (Zepp, 2008). Increased levels of UV radiation to corals can induce bleaching, although it is not clear if this is a direct effect of increased UV exposure or the corresponding increase in sea surface temperature, though a combination of both is most likely (Hardy, Hoge, Yungel, and Dodge, 1992; Bhagooli and Hidaka, 2004; Brown and Dunne, 2008).

4.5.4 Impact Assessment

LIDAR

The energy output of the LiDAR systems and LLS are relatively low and would dissipate rapidly before reaching the depth where exposure occurs (Figure 4). While damage was observed to low light acclimated organisms, the light intensity and exposure times are vastly higher than what would be observed with LiDAR or LLS exposure. The small amount of energy emitted from the LiDAR/ LLS systems, coupled with exposure times limited to a single exposure, suggests no potential hazard to benthic invertebrates. Additionally, potential exposure would be further diminished by attenuation through the water column, especially for airborne LiDAR. In the case of LLS where exposure potential to benthic organisms is higher due to subsurface deployment no negative impacts are expected. Even with the system being closer to the benthic organisms LLS systems are typically deployed between 3 and 9 meters above the seafloor, for which the minimal initial energy intensities would decrease to 74 and 41% of initial output, respectively (NOAA, 2001; Figure 4).

UV Biofouling Prevention System

Although UV attenuation values are higher than observed at 532 nm (Figure 4), the close proximity to the coral and the potential for multiple exposures over an extended time may result in unhealthy stress to the corals. Based on a disparity of empirical data of the effects of UV LED light on corals, coupled with a long-term exposure at a close range, it is unclear if the biofouling prevention system will have any environmental impacts on coral reefs. Further study is needed before the system is recommended for deployment.

5. CONCLUSIONS AND RECOMMENDATIONS

Laser systems play an important role in a diverse range of Navy activities, including mine detection, mapping, oceanography, and communications. The continuation of research and development efforts on underwater laser systems will further enhance Navy capabilities within these activity areas. It is critical to ensure a timely transition from research and training applications to real-world field settings. The findings within this report should help streamline EIS and PESHE processes by providing data on the environmental safety regarding the use of laser systems within the marine setting.

To determine the potential impact of a laser system to an organism in the marine environment, an assessment pathway with the following four components was developed: (1) laser system specifications, (2) exposure potential**, (**3) damage thresholds, and (4) potential impacts. Literature was reviewed for information related to exposure potential, damage thresholds, and expected impacts. As a starting point, the most conservative, or worst case scenario, values for laser system outputs and exposure potential were used in evaluating biological impact, e.g., direct exposure with no energy attenuation.

Most laser systems fall within the blue/green spectrum and include LiDAR, LLS, and submarine communication systems. LiDAR currently is the most widely used laser technology and is applied for mine detection, mapping, and various other activities. LiDAR also offers the greatest exposure potential, versus other systems within the blue/green wavelengths, based on the energy per unit area. The general LiDAR system specifications are similar across the various applications and are designed to meet human safety standards. Marine mammals and sea turtles are most susceptible to ocular damage through LiDAR exposure because exposure may occur above or near the water surface.

This study builds on and supports the work by Zorn, Churnside, and Oliver (2000), which states that based on species-specific energy exposure at the retina, LiDAR systems designed to meet the human safety standards will be safe to any marine mammal or sea turtle that may be exposed, and could safely tolerate higher single exposure limits. Additionally, LiDAR exposure to marine mammals and sea turtles is considered a rare event resulting from an animal surfacing and being exposed to the LiDAR beam and is a function of site-specific animal densities and training hours. The damage potential to plankton from LiDAR systems is extremely low, using phytoplankton as the most sensitive group. Although specific laser thresholds have not been established for phytoplankton, laser dose experiments by Nandakumar et al. (2003a,b) found moderate survival rates with laser fluences several orders of magnitude higher than a LiDAR system, with multiple exposures over longer time periods.

These findings suggest that LiDAR systems would pose no damage to phytoplankton, and other planktonic forms, and is further supported by a minimal exposure potential based on their temporally and spatially (geographically and within the water column) dynamic nature within the marine environment. Potential damage to benthic communities and corals also are very low based on minimal exposure, low laser energy, and energy attenuation through the water column before exposure. LiDAR systems, as they are currently designed and applied, pose minimal or no environmental risk to various classes of marine organisms including marine mammals, sea turtles, plankton, and benthic communities.

The UV LED biofouling prevention system is the only application in this report, which is recommended for further study before field deployment. This system represents a unique application of an emerging technology for use within a specific ecosystem, and uncertainties must be addressed before environmental safety is guaranteed. Although this technology is not expected to be widespread across all Navy installations, and does not necessarily fall into other laser system categories, its importance to successful coral reef monitoring and range sustainment is paramount. Additional research also is being conducted in underwater acoustics that use lasers as the sound source. The laser ionizes a small amount of water that generates a sound pulse. Research related to environmental and biological impacts of sound represents a substantial and complex field of study, especially as it relates to marine mammals. Assessing potential environmental impacts related to underwater sound was outside the scope of this report.

Laser systems deployed within the marine environment represent a powerful tool set. The use of these tools in a wide range of applications provides critical functionality to the overall Navy mission. The systems currently used result in minimal or no environmental impacts. The scope and application of laser systems continue expand, and further research and procurement efforts should proceed unhindered by environmental compliance for systems using similar operating configurations and procedures.

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14. ABSTRACT

This report assesses potential environmental impacts of laser systems on organisms found living in the marine environment. To accomplish this objective, the major laser systems used by the Navy in a marine setting were defined, Environmental Impact Statements (EISs) for various ranges were reviewed, and naval researchers were queried to determine the most prominent laser system usage. Once the predominant laser systems were identified, a list of biological groups that may be affected was generated. To determine the potential impact of a laser system to an organism in the marine environment, an assessment pathway with the following four components was developed: (1) laser system specifications, (2) exposure potential**, (**3) damage thresholds, and (4) potential impacts. Literature was reviewed for information related to both exposure potential as well damage thresholds and expected impacts. As a starting point, the most conservative, or worst case scenario, values for laser system outputs and exposure potential were used in evaluating biological impact, e.g., direct exposure with no energy attenuation.

15. SUBJECT TERMS

Mission Area: Network Communications

environmental impact statements	light detection and ranging	laser line scan	mapping
mine detection	unmanned undersea vehicle	ultra violet radiation	marine mammals

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