High Energy Laser Weapon Integration Issues for the Future Hellenic Frigate

Antonios Lionis[a] and Andreas Tsigopoulos[b]

[a] *University of Peloponesse; lionisantonios@gmail.com*
[b] *Hellenic Naval Academy, Division of Combat Systems, Naval Operations, Sea Sciences, Navigation, Electronics & Telecommunications Sector, Greece; atsigo@hna.gr*

Abstract. Hellenic Navy is about to make its final decision for a new frigate-class acquisition program. This new ship should possess certain capabilities in order to encounter any threats of the future maritime warfare. An essential technology that must be incorporated, is the High Energy Laser (HEL) weapons, that will allow the new maritime platform to effectively deal with small and cheap threats, such as drones and Unmanned Surface Vehicles (USVs), without being constrained from depth magazine and unfavorable cost exchange ratios. The deployment, though, of a HEL weapon on a maritime platform is a very challenging task due to the size, weight and power (SWaP) requirements as well as due to the various atmospheric effects that tend to degrade its performance. This paper, investigates the requirements for integrating a notional laser weapon on a maritime platform and compares various energy storage solutions, including lithium-ion batteries, lead acid batteries and flywheels. We also examine the deleterious effects of the atmospheric turbulence in a maritime environment on the laser weapon performance. Finally, a new machine learning based approach to predict the performance of an HEL weapon on a maritime platform is presented.

Keywords: High Energy Laser Weapons; Hellenic Navy; energy storage; machine learning

PACS: Replace this text with PACS numbers; choose from this list: http://www.aip.org/pacs/index.html

INTRODUCTION

Hellenic Navy is about to make its final decision for a new frigate-class acquisition program. This new ship should possess certain capabilities in order to encounter any threats of the future maritime warfare. An essential technology that must be incorporated, is the High Energy Laser (HEL) weapons, that will allow the new maritime platform to effectively deal with small and cheap threats, such as drones and Unmanned Surface Vehicles (USVs), without being constrained from depth magazine and unfavorable cost exchange ratios. Talking about laser weapon systems, it is critical to distinct four major functional sub-areas, each of which must be treated and developed separately before we converge all of them to the final product of our system. These include [1]:

a) The laser device itself, which can be either technology among solid state, fiber, gas, chemical or even free electron laser. Each of these technologies possesses pros and cons, but solid state and fiber lasers R&D efforts have been favored the last decade as the ones with the best potential for integration in maritime platforms, especially due to their adequate wavelength of operation for maritime environment and relatively high efficiency as well as their safety comparing to chemical or gas lasers. Their major drawback which still draws the attention of the laser community is the very high thermal management requirements of the waste heat. This problem is not so prominent in the fiber technology because of its high surface-area-to-volume ratio compared to the bulk SSLs.

b) The second area is the control of the beam, which is defined as a multidisciplinary effort to direct the HEL onto the target's vulnerable aimpoint and maintain it there. The necessity to hit the target on a specific aimpoint requires very high image resolution capabilities, a stable platform and extreme precision. The beam control hardware components include the illuminators, the beam corrector and relay optics, the beam control sensor and the beam director.

c) The third area is the deleterious effects that the various atmospheric phenomena have on the laser beam. The most significant of them for a high energy laser beam, is the atmospheric extinction, including absorption and scattering, the atmospheric turbulence and the thermal blooming. Here, we will focus on the atmospheric turbulence effects, which can significantly degrade the performance of an HEL weapon, especially for longer distances.

d) Finally, the interaction of the laser beam with the target (laser lethality) which involves four basic stages: (1) the absorption of laser radiation by the target materials, (2) the redistribution of the energy into various material responses such as heating, radiation and ablation, (3) the response of the material such as thermal penetration, rupture and fracture, and (4) response of the system as a whole. In order to produce damage there must be a strong coupling of the laser light to the target, which is a function of the wavelength, the target materials and the angle that the target presents to the beam.

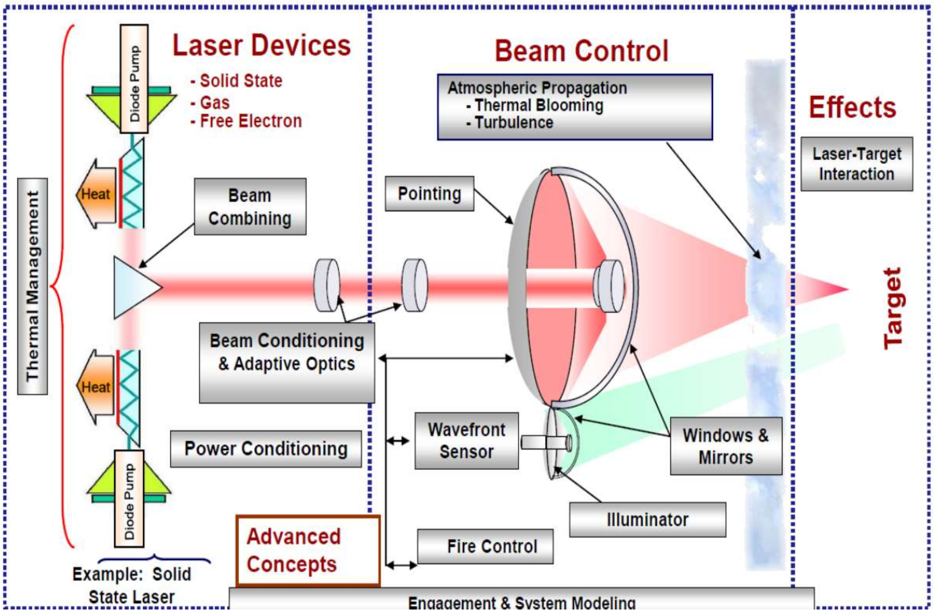

FIGURE 1. HEL – JTO Technology Thrust Area [2]

ADVANTAGES AND DISADVANTAGES OF HEL TECHNOLOGY

Apparently, the above mentioned sub-areas of laser weapons are highly dependent to each other and an excellent synergy must occur among them in order to achieve the best result. Potential advantages of shipboard lasers include the following [3]:

a) Precision of their lethal energy. HELs deliver their amount energy (up to several MJs) at several kilometers of range without risking any collateral damage.

b) Very fast engagement. The laser beam reaches a target with the speed of light (therefore no intercept course exists) and, disables it after a few seconds of focusing in a certain point on its surface and then re-engage another target.

c) Ability to counter radically maneuvering missiles. Lasers can follow and maintained locked on target with very high maneuvering capabilities, such that a standard SAM would not be able to follow.

d) Graduated responses. Lasers are able to cause a wide range of effects to their targets, offering the unique capability of non-lethal effects.

e) HELs do not require any explosives so they are considered safer than their kinetic counterparts.

f) They have very large magazine depth and very low cost per engagement.

The latter one will be further discussed later, since it is the major driver for HEL deployment on maritime platforms.

Accordingly, the laser weapon systems technology presents several limitations, some of which can cause significant performance degradation. These limitations include [3]:

a) Line of sight requirement. The path of the laser beam is considered almost straight, therefore targets beyond the line of sight of the HEL cannot be fired. Additionally, targets that are covered are also protected from an HEL weapon hit.

Therefore, small surface targets can be obscured from big waves for a certain amount of time.

b) Limited by saturation attacks. Each target engagement requires a certain amount of time (up to several seconds) to be degraded, therefore no other target can be engaged at the same time. This sets an upper limit on the ability of an individual laser to deal with saturation attacks. This limitation can be mitigated by installing more than one laser on the ship, similar to how the US Navy installs multiple CIWS systems on certain ships.

c) Atmospheric effects. Air molecules and aerosols in the atmosphere absorb and scatter light from a shipboard laser, and atmospheric turbulence can defocus a laser beam. These effects can reduce the effective range of a laser. As shown in Figure 2, certain operational wavelengths exist that allow better transmittance of the laser beam. Therefore, the selection of these wavelengths is preferred since they favor the performance of an HEL. Adaptive optics, can mitigate the deleterious effects of optical turbulence by continuously adjusting the wave front of the beam.

d) Thermal blooming effect. The continuous firing of the laser in the same direction causes the ambient air to heat up, resulting in beam defocus. Therefore, targets approaching from a constant direction may cause an HEL to be less effective. Typically, thermal blooming effect becomes more significant as HEL output power increases, at the hundreds level.

e) Performance dependent on target characteristics and countermeasures. Apparently the effectiveness of the HEL is not just a parameter of its design characteristics and atmospheric effects, but also to the resistivity that the target's surface can demonstrate to certain wavelength EM waves. A variety of reflective materials and surfaces can protect the target from the required energy accumulation, thus destruction. Other obscurants can be employed, such as smoke, to leverage on the deleterious atmospheric effects and further decrease the laser beam's coherence.

f) Risk of collateral damage. The laser beam's path of an HEL looking upward, would endlessly continue traveling if it does not hit a target, endangering that way other flying objects. Additionally, the laser beam can cause severe damage to human eye, therefore pilots that cross a laser beam in the air are at high risk.

Apparently, the DE weapons do not intend to replace kinetic weapons but rather complement them.

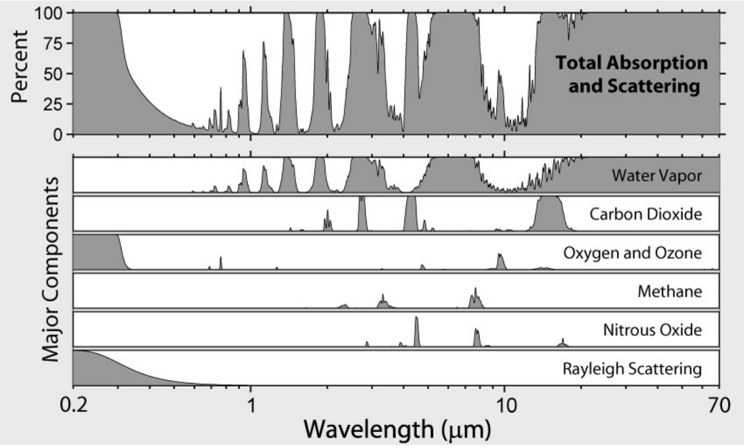

FIGURE 2. Transmission "windows" versus laser wavelength. [4]

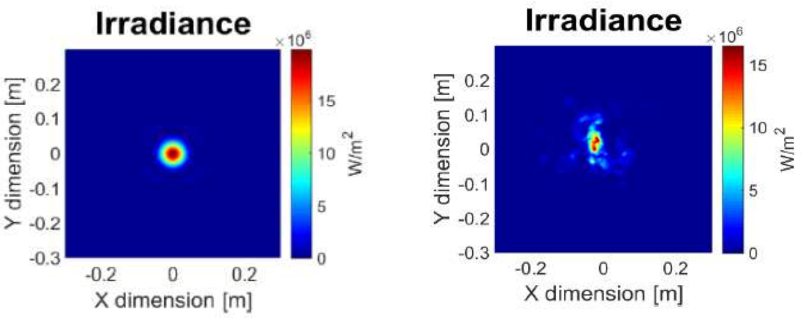

FIGURE 3. The optical turbulence effect on a laser beam as compared to a perfect Gaussian beam [4]

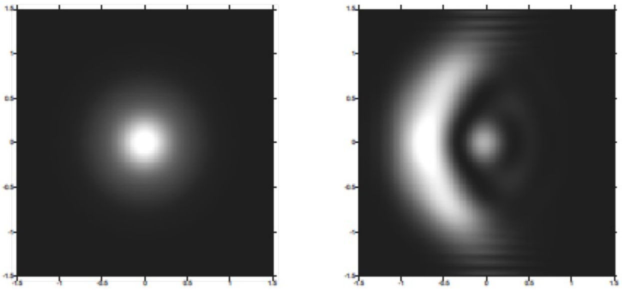

FIGURE 4. The thermal blooming effect on a laser beam (right) as compared to a perfect Gaussian beam [4]

HEL FOR MARITIME PLATFORMS

The two major limitations that surface ships currently have concerning their defense against missiles and UAVs are limited depth of magazine and unfavorable cost exchange ratios. A typical Navy surface ship are able to carry a certain amount of surface-to-air missiles (SAMs) and ammo for their close-in weapon systems, with which they can be protected from air targets, such as UAVs. Once this load is expended the ship is required to be suspended from battle in order to be replenished. This task would require a significant amount of time [3].

Unfavorable cost exchange ratios refer to the significant difference between the cost of a SAM procurement and the cost of a small to medium UAV. This cost difference makes unfavorable the engagement of a small and cheap UAV with an expensive SAM, ranging from several hundred thousand dollars per mission to a few million dollars per missile, depending on the type. Laser weapons, and especially SSLs, inherently can provide a perfect solution to overcome these two limitations. SSLs are electrically powered devices, pumped directly from the ship’s power plant. That being said, since the ship is able to provide the required electrical power to the HEL, the latter can fire relentlessly. Consequently, the cost of firing an HEL is equivalent to the cost of the fuel needed to generate the electrical power used during fire. Hardly ever this cost would exceed the one dollar per shot. Most likely, since the required power levels to destroy a small boat or a UAV as compared to those for a missile destruction are significantly different, an HEL weapon can complement the kinetic weapons by focusing on the former type of targets, while SAMs to the latter.

Major Current HEL Development Programs

The major current programs for developing and integrating a laser weapon in maritime platforms include:

a) The solid state laser – technical maturation program, which aims to develop and integrate a Laser Weapon System demonstrator has been installed on an LPD during 2019. This system, according to the US Navy's FY 2021 budget submission, would provide a new capability to the fleet against asymmetric threats and will inform future acquisition strategies for laser weapon systems [3]. The demonstration on the LPD is to continue through FY2022 and the system is to be de-installed in early FY2023. The program is led by the Office of Naval Research and Northrop Grumman and officials talk about a laser system with an output power up to 150kW which has used the gained experience from the previous major Navy laser weapon program, the so-called LaWS, installed and tested on USS Ponce from 2014 to October of 2017. On May 22, 2020, the Navy announced that Portland had used its LWSD to successfully disable a UAV in an at-sea test that was conducted on May 16, 2020.

2) The Optical Dazzling Interceptor, Navy (ODIN) a government designed, developed and produced system which aims to provide near-term directed energy, shipboard Counter-Intelligence, Surveillance, and Reconnaissance (C-ISR) capabilities to dazzle Unmanned Aerial Systems (UASs) and other platforms that address urgent operational needs of the Fleet. ODIN has already been installed in an Arleigh Burke-class destroyer from 2019 as a stand-alone unit and is the first operational deployment of a laser dazzler that can temporarily degrade intelligence gathering capabilities of unmanned aerial systems. Unfortunately, there is a highly restricted information availability about its specifications [3].

3) Surface Navy Laser Weapon System, also known as HELIOS, meaning a high energy laser with integrated optical dazzler and surveillance. The goal of this program, is the development and rapid fielding of a 60 kW-class high-energy laser and dazzler in an integrated weapon system, for use in countering UAVs, small boats, and ISR sensors, and for combat identification and battle damage assessment. The contract has been awarded to Lockheed Martin and refers to two systems with an option of 14 additional systems. This laser weapon system is again intended to be installed on an Arleigh Burke-class destroyer [3].

4) The High Energy Laser Counter-ASCM program, an effort to leverage the knowledge gained from the previous mentioned programs and develop a high energy laser weapon with more than 300-kW of output power, capable of defeating Anti-Ship Cruise Missiles by addressing the remaining technical challenges such as atmospheric turbulence, automatic target identification and aim point selection, precision target tracking with low jitter and advanced beam control [3].

5) European activities, include the Tactical Advanced Laser Optical System (TALOS), led by CILAS and include 16 participants from 9 countries. TALOS aims to provide the framework necessary for future R&D actions, generating a roadmap to develop critical laser effector technologies and ensuring strategic autonomy and security of supply. The project will also develop and demonstrate some of the most critical Laser Directed Energy Weapon technologies paving the way to the design and build of an EU high-power laser effector to be integrated in military applications in the next decade. The technologies to be demonstrated include elements of the high-

power laser source, atmospheric turbulence compensation and precision target tracking and laser pointing systems.

Considerations for HEL Integration Issues in Maritime Platforms

Placing a High Energy Laser weapon system in a moving platform, requires that several design characteristics must be considered in order to estimate the total impact of the weapon's integration to the specific platform. That being said, we distinguish the pure performance requirements of the HEL with the integration requirements to a naval platform. A system that meets the former but fail to meet the latter, is useless. The major constraints of an HEL are the Size, Weight, and Power (SWaP) as well as the cooling requirements [5].

To give an estimate of the power requirements, we need to define the wall-plug efficiency of a laser weapon. That is the ratio of the output power to the input electric power, with the required power for pumping the gain medium, remove the heat, computer and diagnostic subsystems, power supply and conversion losses to be included. A current nominal value of the wall-plug efficiency of the modern HELs is approximately of 25%, therefore a total input power of 120kW is required for a 30kW laser weapon.

Referring to the size of an HEL, we could approximate it as the size of a small refrigerator for a 5 kW single mode fiber laser, which would scale linearly with the output power [4]. This excludes the size of external power and energy storage subsystem, the beam transport, beam combining, beam director, target and tracking sensors. The estimated volume of a 100kW weapon would likely be on the order of $100m^3$ [5].

The weight of a laser weapon includes, the weight of the beam director, the laser system weight, the power supply weight and the thermal management weight. Apparently, the lower the wall-plug efficiency, the higher the total weight of the system.

The power required to fire an 100kW HEL weapon with an efficiency of 25% would be 400 kW. Assuming a 5 seconds laser fire a total of 2 MJ of energy would be required. Unfortunately, currently such amount of energy is not available in most ships. That means that a separate energy storage system is necessary and we discuss about it in next paragraph.

The cooling requirements, is a major limiting factor for most HELs. Consider a 100kW laser with 25% wall plug efficiency, then it takes 400 kW of power to create 100 kW laser beam. That means we must manage 300 kW of heat. Supposing laser fires of 10 seconds then the water needed to absorb this heat can be computed using this formula, with the assumption that the water density is approximately 1kg/L. Then, our cooling requirement would be a liter of water each second.

Sustainment and Manning

To retain a system fully operational throughout its lifecycle, a thorough sustainment plan is required, including guidance in the following activities [5], a) preventive maintenance, b) system assessment for proper operation, c) operational logs review for issue indication, d) supportability requirements. Engineering the sustainment of a system relates all the technical tasks to ensure its reliability from the needs analysis phase till its disposal. An import design characteristic of the system which relates directly to sustainment is the used materials. The major components of a typical SSL include the medium, the optical equipment, flash pumps or diodes, and amplifiers. The operation of such components in a maritime environment requires special attention. For example, the optical equipment needs to be cleaned very good, because micro particles can severely affect the quality of the beam and cause damage to the optical coating. To do so in a maritime environment, where salt, aerosol and humidity quantities are increased, is very challenging and requires special equipment. This is not the case for fiber optic laser weapons, since they use only fiber optics. On the other hand, SSL can be more easily maintained onboard a ship, since they use sealed line replaceable units, therefore, do not require depot level maintenance. Additionally, proper cover should be placed in order to protect the elements from exposure to the environmental conditions. The system also requires a stabilization unit, so it remains always steady onboard a maritime platform which is in continuous motion. Reasonable availability of specific oil or grease must exist, because the mechanical parts of the weapon must always be lubricated. The more testing equipment the ship has onboard, the more the weapon's availability increases since a failure cause will be easier found and fixed. However, some components require high levels of expertise, are extremely sensitive, or large in size discouraging storage onboard a ship. Proper markings and signs on the weapon's area is required to warn somebody about the dangers inherent to DEWs. The operators of the HEL need to have protective gear, especially for their skin and eyes. The eye protection is dependent on the certain wavelength of the system.

In a dynamic global environment, military forces must be organized, equipped, and trained in such a way, so they can employ the most technologically advanced equipment, tactics, and procedures instantly. Adequate knowledge of the procedures and tactics regarding the reaction against any threat, will ensure higher readiness and efficiency, which can also be facilitated by proper manning and training of the operators. Smart systems to control and monitor energy consumption, as well as the health of critical systems, can support both manning and resource conservation. Proper training and reliable user interfaces will assure more effective use of platform resources and reduced operational cost. The education of the operators in fundamental DE concepts, such as generation, attenuation and propagation must be rigorously taken care, because they will maximize the effectiveness of the system's employment. Concepts such as temperature, pressure, humidity and other considerations such as optical turbulence or thermal blooming effects, are areas where operators should be trained to ensure that they are proficient when using such a high end system [5]. Training is one of the elements that have a very high return on investment.

HEL Location Evaluation Criteria

The exact location of an HEL weapon onboard a maritime platform depends upon five criteria, a) shipboard operations, b) atmospheric turbulence, c) environment, d) azimuth coverage, and e) elevation coverage [6]:

a) Shipboard Operations: The distance between other weapon systems of the platform, such as a gun or a missile launcher and the HEL is a critical parameter for possible introduction of jitter disturbances. This effect will cause a severe performance degradation of the laser weapon.

b) Optical turbulence: The temperature difference between the ambient air and the air heated by the ship's deck cause changes in the air refractive index and consequently optical turbulence. Therefore, the distance traveled by the beam over the ship's deck will determine the turbulence effect strength. This effect, may potentially be worse than the equivalent over water.

c) Environment: The surrounding environmental conditions may be affected by the exhaustions of the ship's engines. Therefore, a laser beam traveling over these exhaustions will encounter very deleterious effects and performance degradation will occur.

d) Azimuth and Elevation Coverage: As a strictly line of sight weapon, the HEL, may be considerably limited by surrounding superstructures of the ship. Therefore, higher locations with as higher as possible azimuth and elevation coverage are desirable.

Energy Storage Options

As mentioned in the previous section, an electrically driven HEL weapon can fire against its target with a cost of as low as one dollar, given that it's platform can provide it the adequate electrical power for as long as it shoots. The amount of power required for the time of lazing the weapon is such that an energy storage system is needed in order to have available the required energy to shoot, since the ship's electrical power won't be sufficient [7].

Many different types of energy storage technologies exist, including batteries and flywheels. The most important performance parameter of an energy storage system is its energy and power density. Energy density is the amount of energy that can be stored compared to the weight or size, while power density is how quickly the stored energy can be released compared to the weight or size. Apparently, maximizing both of them would be ideal, but this is not the case and tradeoffs must be made based on the use case scenarios of the specific HEL weapon [7].

The first option would be the lead acid batteries, which provide a mature and safe solution and already exist on board Navy ships. Their energy density is relatively high (~200 MJ/m^3) whereas their power density is pretty moderate. A significant advantage of lead acid batteries is that it takes several hours to recharge but should not be discharged lower than 50 percent because this will lead to reduced life cycle [8].

Another option is the lithium-ion batteries, which have even higher energy density (~1000 MJ/m^3), higher discharge tolerance (~80 to 90 percent) and recharge faster than lead acid batteries. The higher energy density of lithium-ion batteries results in a much less overall weight and volume than that of a lead acid battery. Their main disadvantage is that they are known to be potential fire hazards, which could make their relevance as an energy storage system full of pitfalls [8].

Finally, a third alternative are the flywheels, is a device rotating at very high speeds (~60,000 rpm) and convert the mechanical to electrical energy. They have comparable energy density to that of batteries but much higher power density. Their main advantage is their ability to charge and discharge very fast, providing an optimum solution for multi-shot engagements. This requirement is obvious when swarm attacks take place. A disadvantage of this alternative is that it is not a commercial of the shelf (COTS), therefore it must be specifically designed for the platform [8].

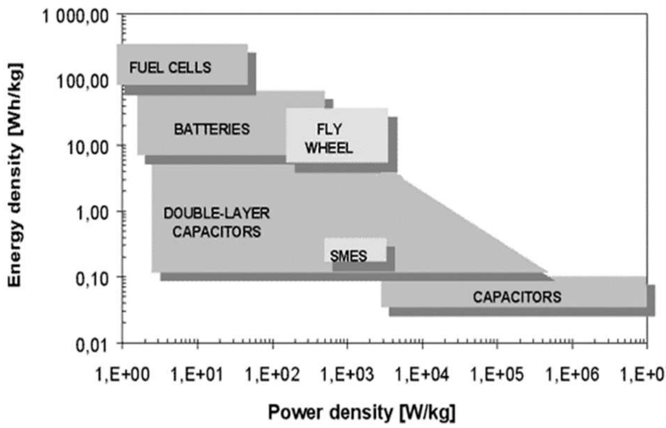

FIGURE 5. Energy density versus power density for various energy storage alternatives [4].

Atmospheric Effects

In addition to the inherent attributes of a high energy laser weapon system, in order to estimate its actual effectiveness in terms of its ability to “kill” a target, we need to take into account a) the laser beam propagation through the atmosphere and b) the effects of the delivered energy to the target. The former is primarily a factor of the laser’s wavelength and the existing atmospheric conditions between the HEL weapon and the target, whereas the latter is a factor of the material of the target [9].

The earth’s atmosphere is divided by four distinct layers in terms of temperature difference on various heights. The two lower layers, troposphere and stratosphere, have the most significant effects on a laser weapon system. The atmosphere is primarily composed of gaseous molecules and aerosols. As the laser beam travels through the atmosphere, these micro particles are responsible for its degradation due to effects of absorption and scattering. These two effects combined are called the extinction effect. In order to determine the total extinction, we need to know the extinction coefficients at each point along the beam path. However, these change with location, altitude, season and time of day and make its calculation a very difficult task, so a wavelength that falls into a transparency window is required in order to minimize this effect [9].

As the laser beam propagates through atmosphere, the index of refraction of the surrounding air mass alters due to the air temperature increase and consequently the beam deviates from its initial direction. This effect is called thermal blooming and, as mentioned, is a direct result of absorption. The higher the power and focus of the laser beam, the higher the effects of thermal blooming.

Another atmospheric phenomenon that can radically affect the laser beam propagation is the atmospheric turbulence. It is almost impossible to predict the turbulence in a specific point around space due to its significantly nonlinear nature; rather, scientists use a statistical approach to estimate the overall effects of turbulence on a macroscopic scale. A laser beam propagating through atmosphere is affected by turbulence due to vertical temperature and density variations. The temperature and density differences result in changing the air refractive index, and consequently the propagating beam is distorted due to induced amplitude and phase fluctuations [9].

MACHINE LEARNING-BASED TURBULENCE MODELING

Prediction of the atmospheric turbulence in the low-altitude maritime environment is a very challenging task. However, it is very critical for the performance of the laser weapon, therefore several methods have been applied for its modeling [10].

We have selected a machine learning based approach, and specifically an artificial neural network, to relate macroscopic atmospheric parameters with the refractive index structure parameter, C_n^2 that gives the strength of the turbulence phenomenon. Collecting macroscopic atmospheric parameters such as ambient temperature, pressure, relative humidity etc is a simple task and can be done through a mobile weather station. However, modeling the C_n^2 parameter using atmospheric parameters can be a very complex task. And here comes in play artificial neural networks [10].

Machine learning for laser propagation is an emerging topic that will certainly gain more interest in the near future. Machine learning includes a broad spectrum of tools that allows interpretation and understanding of data through a trained algorithm. Supervised learning algorithms are trained using labeled examples, such as an input where the output is known and is focused on estimating the function f that relates the output with the input values. Having estimated f, one can predict the output for a specific set of input variables.

The performance of an HEL over maritime environment exhibits significant differences with a terrestrial one. Such a difference is the typical diurnal profile of the atmospheric turbulence between a terrestrial and an over-water propagation path, where the latter does not exhibit reduced values around sunrise and sunset as is the case for the former. That means that the C_n^2 strength does not follow the characteristic bell-shaped diurnal profile but a random one during the day. Additionally, the C_n^2 strength over water is generally an order of magnitude lower than over land. Over water, the atmospheric structure constant was found to have a strong dependence on the air-sea temperature difference (ASTD). Additionally, different beam propagation characteristics were observed for each temperature gradient sign. For colder air temperatures the beam transport is improved [10].

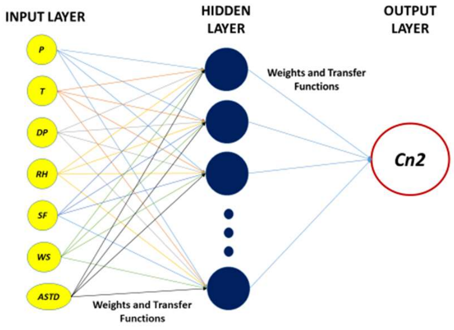

FIGURE 6. A single layer perceptron model for C_n^2 prediction [10].

Hellenic Naval Academy Experimental Site

Over the last few years, the Hellenic Naval Academy conducts a significant research effort towards optical turbulence characterization and modeling as well as experimental performance analysis of laser systems over maritime environment [11,12]. The experimental instrumentation is located on the roof of the Hellenic Naval Academy (HNA) (primary terminal) and the lighthouse of Psitalia island (remote terminal). The horizontal optical link is located 35 meters above the sea and crosses the entrance of the Piraeus port; nearly the entire path is over the water. The upper figure shows the exact spots of both terminals in the map as well as the ambient environment that the 2958 m long optical link operates. The FSO system used in the experiment was an MRV TS5000/155 model. The setup consisted of two terminals both of which, utilized stand-alone PCs in order to send and receive/store data. The interface between them is achieved through an SFP multimode fiber cable, operating at 1310nm, which drives the optical signal from the detector through an O-E converter directly to the PC. The RSSI data is then stored and is available to export for further analysis. The terminal over Psitalia island can be remotely operated from the HNA through the optical link. Additionally, an Ambient Weather (WS-2000) weather station is co-located with the HNA FSO terminal to provide real time macroscopic meteorological parameters. These measurements are then stored and readily available to export and analyze. In the near future a Scintec BLS450 boundary layer scintillometer will also be added to the experimental setup and will provide real time atmospheric turbulence and heat fluxes measurements.

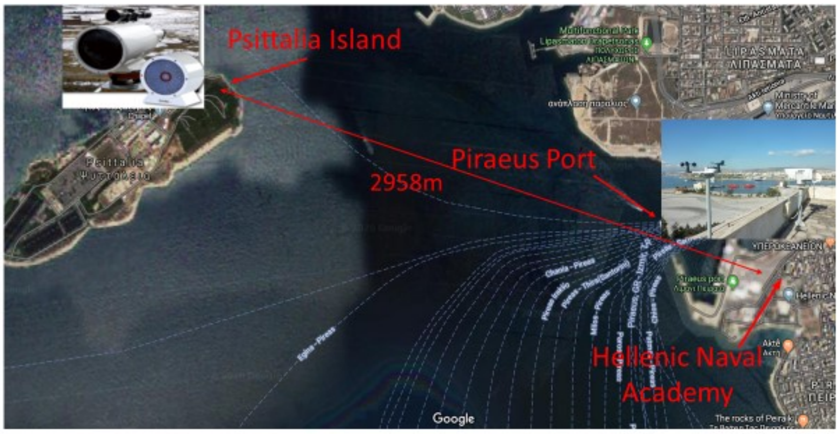

FIGURE 7. **The maritime optical communications link that connects the Hellenic Naval Academy and the lighthouse on Psitallia Island and has a total length of 2958 meters [10].**

CONCLUSIONS

A brief overview of the advantages and disadvantages of the HEL weapons is given. Two are the main drivers for HEL integration in maritime platforms, the unlimited magazine depth and the favorable cost exchange ratio. Current developmental programs for maritime HEL weapons in USA and Europe are presented. The major integration issues for HEL weapons in maritime platforms are identified as the SWaP and cooling requirements constraints. Rough estimations on size, weight, power and cooling requirements for a HEL weapon are given. Other important technical issues, namely the sustainment and manning, referring to the lifecycle of the system are also discussed. Five criteria for the exact location of the HEL weapon onboard a maritime platform have been identified, in order to achieve the best operational outcome and three alternative energy storage systems are presented. Finally, a new machine learning based approach for optical turbulence prediction is presented.

REFERENCES

1. Perram, G. P., Cusumano S. J., Hengehold R.L. and Fiorino S.T. 2009. *Introduction to Laser Weapon Systems*, 1st ed. Albuquerque, NM: Directed Energy Professional Society.
2. Recent Developments and Current Projects in HEL Technology. High Energy Laser – Joint Technology Office (HEL-JTO). February 2012.
3. O’Rourke, Ronald. 2021. Navy lasers, Railgun and Gun-Launched Guided Projectile: Background and issues for Congress. CRS Report No RL44175. Washington, DC: Congressional Research Service. https://fas.org/sgp/crs/weapons/R44175.pdf
4. Blau, Joe 2020. PH4858 Electric Ship Weapon Systems. Lecture, Naval Postgraduate School, Monterey.
5. D. Ciullo et. al, “Viable Short-term Directed Energy Weapon Naval Solutions: A Systems Analysis of Current Prototypes”, MSc, Capstone Project Report, Naval Postgraduate School, 2013.
6. S. J. Gildmeyer et. al., “Analysis of shipboard effects and coverage for the integration of a HEL on a LPD 17”, MSc, Capstone Project Report, Naval Postgraduate School, 2018.
7. J. E. Sylvester, “Power Systems and Energy Storage Modeling for Directed Energy Weapons”. MSc Thesis, Naval Postgraduate School, 2014.
8. J. H. Valiani, “Power and Energy Storage Requirements for Ship Integration for Solid-State on Naval Platforms”. MSc Thesis, Naval Postgraduate School, 2016.
9. A. Lionis, “Experimental Design of a UCAV-based High Energy Laser Weapon”, MSc Thesis, Naval Postgraduate School, 2016.
10. A. Lionis et. al. 2021. Using Machine Learning Algorithms for Accurate Received Optical Power Prediction of an FSO Link over a Maritime Environment. Photonics 2021, 8, 212. https://doi.org/10.3390/photonics8060212
11. Lionis, A.; Peppas, K.; Nistazakis, H.E.; Tsigopoulos, A.D.; Cohn, K. Experimental Performance Analysis of an Optical Communication Channel over Maritime Environment. *Electronics* **2020**, *9*, 1109.
12. Lionis, A.; Peppas, K.; Nistazakis, H.E.; Tsigopoulos, A.D.; Cohn, K. Statistical Modeling of Received Signal Strength for an FSO Channel over Maritime Environment. Opt. Commun. 2020, 489, 126858, doi:10.1016/j.optcom.2021.126858.