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Applications of Lasers for Tactical Military Operations

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***Abstract*— Laser technology has observed a great advancement over the last few decades. This technology is used for a wide range of applications including medical sciences, military, industrial manufacturing, electronics, holography, spectroscopy, astronomy and much more. Military operations often demand a secure and timely transmission of a massive amount of information from one place to another. Until now, the military has relied on the radio spectrum for effective communication, which is vulnerable to security threats and susceptible to electromagnetic interference (EMI). Also, this spectrum is hard-pressed to meet the current bandwidth requirement for high-resolution images, on-air video conferencing and real-time data transfer. Therefore, the focus has shifted to visible and infrared (IR) spectrum using laser technology which is capable of providing secure data transfer because of its immunity to EMI. The probability of intercepting a laser signal is very low due to its narrow beam divergence and coherent optical beam, making the laser a suitable candidate for secure military tactical operations. Besides the communication aspect, the highly directive nature of a laser beam is also used as a directed energy laser weapon. These highly powerful and light weighted directed energy laser weapons are very cost-effective countermeasures for airborne threats. Furthermore, laser sensors are deployed in the battlefield or in space for tracking the path of a wide range of military vehicles like missiles, unmanned aerial vehicles (UAVs), fighter aircraft, warships, submarines, etc. Advancements in space operations and laser technology have offered synergistic possibilities of using lasers from space-based platforms during military operations.**

In this paper, we are providing our readers with a comprehensive study of laser applications, used by the military, to carry out tactical operations on the ground or space-based platforms. Also, an intensive investigation on the development of laser technology for sensors, range-finders and target designators that are used for intelligence, surveillance and reconnaissance (ISR) is presented in the paper. The advancement of laser communication for military purposes and its current state of the art is reviewed as well as some recent scientific developments in the area of high-energy directed laser weapons are discussed, which have revolutionized military battlefields. Therefore, this manuscript highlights recent trends and engineering breakthroughs for the use of lasers in tactical operations.

***Index Terms*—Laser communication, laser range finders, laser sensors, laser weapons, jamming, data relay, ultraviolet communications, hybrid optical/radio-frequency link, weather modification, holographic projection.**

I. INTRODUCTION

Laser technology has observed great scientific developments and engineering improvements that make it usable for various commercial, industrial, medical and scientific applications. The lasers have already brought great benefits in photography, spectroscopy, holography, data storage, surgery and much more. It uses the phenomenon of stimulated emission to generate a coherent optical beam that offers a wide variety of functionalities for various applications. There are variety of lasers available in the market today with different wavelengths, spectral bandwidth, power levels, operating efficiencies and temporal characteristics. This increasing maturity of lasers and compact optical systems have enhanced their capabilities for military operations. Military officials have indubitably always been interested in laser technology, even before the first laser was invented. Especially, since these devices can bring technological revolution in warfare, when used as range-finders, target designation, sensors, active illumination, data relay devices, directed energy weapons, weather modifier and much more. Ever since the first demonstration of laser by flashing light through a ruby crystal in California's Hughes Research Laboratory in 1960, it took almost 50 years to bring them for practical use in the battlefield [1]. From the 1970s to mid-1990s, the use of radio frequency (RF) along with digital signal processing techniques has shown dominance in military warfare. However, RF is not capable of handling the ever-increasing demand of information in military operations that uses electronic warfare systems, spread-spectrum communications, wide bandwidth radar systems, etc. For all these military applications that require huge capacity and real time processing over wide dynamic ranges, lasers are considered a good choice over RF signals. Over the years, laser technology has sufficiently matured to provide cost-effective, energy efficient, high-speed and wavelength-flexible systems that can be used for a variety of military operations such as commutation, remote sensors, directed energy weapons, etc.

The laser technology offers several benefits over conventional RF or microwave systems for tactical operations. Although traditional RF and microwave frequencies are excelling on many fronts, they become vulnerable or non-effective under certain scenarios such as real-time threats, tapping, jamming, low bit rate, high latency, large size, weight and power (SWaP). Since the bandwidth provided by the optical system (due to high carrier frequency) is much higher than the radio or microwave systems', lasers are capable of disseminating large volumes of data or video information in the battlefield, often in real time. Successfully demonstrating

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data transfers, with bit rates up to Gbps, various commercially available products are found with many different companies, such as AOptix Technologies in California, LightPointe wireless in San Diego, fSONA Systems and Plaintree systems in Canada or SkyFiber Inc. in Texas. Laser communication link is more secure than RF link due to its coherence and narrow divergence of optical beam. By virtue of short wavelengths, the optical beams can travel longer distances along a line-of-sight (LOS) path that cannot be easily intercepted. Laser technology has the ability to provide communication link at data rates comparable to fiber-optic links without the need of digging optical fibers over long lengths or spectrum licensing. Further, if the carrier wavelength is chosen to be in the invisible spectrum, it becomes even harder to detect or intercept a laser beam unless there is any electro-optic (EO) system place in the path of the beam. Also, owing to the larger gain of optical carrier wavelengths, laser-based communication systems can outperform RF systems in terms of lower SWaP requirements. This makes laser technology more suitable for tactical operations from space at very low cost.

Lasers are also used as directed energy weapon to cause substantial damage to the target. High power laser beams can be used to hit the target over hundred of miles with good precision and accuracy. Lots of extensive research is going on in the field of high-energy laser weapons [2]–[5]. A high power airborne laser turret developed by US Defense advanced research projects agency (DARPA) and Air Force research laboratory (AFRL) is a good example of their success in space-based lasers technology [6]–[8]. Countries like Russia, China, Germany, India and Japan are also doing extensive developments on laser weapons. Similarly, lasers utilizing low power levels are used to blind or confuse the missiles, instead of destroying them [9]. High-energy lasers have the potential to be used as illumination devices, active imagers or power beamers to recharge the batteries of satellites or to deliver energy to a distant location on Earth. Some of the leading companies that play a vital role for military laser technologies are BAE Systems, Lockheed Martin, Northrop-Grumman, Raytheon and Boeing.

The rest of the paper is organized as follows: Section II highlights some of the past and recent developments in laser technology. Various laser types and their military applications are presented in Section III. Finally, concluding remarks are given in Section IV.

II. HISTORIC PERSPECTIVE

Laser technology has been used in military operations for applications including laser weapons, communication, remote sensing, information relaying, active imagers, illuminators, etc. Various scenarios where laser technology can be used for military operations are: air-to-ground/ground-to-air, air-to-air, ground-to-ground, space-to-space, ship-to-ship/ship-to-shore, ground-to-satellite, inter-satellite or underwater-submarine systems. Some of these systems have been experimentally demonstrated but none have been considered as a standard for military operations until date [10], [11].

During the 1970s, US Air Force initiated a 405B program to develop a laser communication link (up to 1 Gbps) between geostationary satellite and ground station. The program successfully transmitted and detected a modulated laser beam by engineering feasibility models developed by McDonnell-Douglas. Later, in 1975, the space flight test system (SFTS) program demonstrated a high capacity transmission, both to a ground terminal and low-earth orbit (LEO) terminal [12]. During this era, a vast development and proliferation of laser technology has been observed in the support of the defense programs [13]–[17]. In the 1990s and early 2000s, various comprehensive studies were carried out for use of lasers to military missions such as laser mission study (1991) [18], new world vistas (1995) [19], cross-link studies for the follow-on early warning system (FEWS) program, which later became the space-based Infrared system (SBIRS, halted in 1993) [20], lasercom inter-satellite transmission experiment (LITE) [21], terahertz optical reach back (THOR) (2002) [22], optical RF combined link experiment (ORCLE) (2004) [23] and transformational satellite communication system (TSAT) (canceled in 2009 due to cost and delay factors) [24]. Later in 2010, fast airborne laser communications optical node (FALCON) carried out research in collaboration with AFRL and Exelis, Inc. for developing 2.5 Gbps full duplex optical link between two aircraft [25]. In 2013, German-based company ViaLight achieved success in demonstrating 1.25 Gbps link between a mobile jet aircraft and a transportable optical ground station (TOGS) over a distance of 50 km [26]. Up till now, data rates approaching 100 Gbps have been demonstrated over short distances from airborne platforms. Tactical line-of-sight optical network (TALON), which was developed in coordination with the Naval Research Laboratory (NRL), is working towards transmission of large volumes of data from ship-to-ship or ship-to-shore or vice versa. They successfully demonstrated wireless transmission of high resolution images and videos up to 100 Mbps over a distance of 31 miles [27]. This would provide a secure and reliable technology for the transfer of ISR data between two mobile ships. In order to enhance the reliability and data capacity for faster coordination with nearby aircraft and submerged submarines for anti-submarine warfare (ASW), the military is carrying out extensive researches on blue-green submarine laser communication. Some of the ongoing and recent laser projects for the military operations (after the year 2010) are found in Table I .

III. LASER TYPES AND THEIR POTENTIAL MILITARY APPLICATIONS

The types of lasers for military operations vary according to the environment and the mission for which they are used. Various parameters are used to classify lasers for diverse range of applications are: output power, operating wavelength, beam cross-sectional area at the point of interest, accessible emission limit and exposure duration. For example, lasers used for tactical military communication with very low probability of interception/detection requires high-energy collimated laser beam and adjustable beam divergence in order to avoid spillage of the signal beyond the target receiver. Further, the

Table I: Various programs/projects for demonstrating laser technology in military operations

Program name/Title	**Purpose**	**Comments**	**Ref**
Lunar Laser Communication Demonstration(LLCD)	Communication	This is a joint project between Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), California Institute of Technology and the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) that aims to provide high data rate with low power and mass requirements. They demonstrated 622 Mbps (downlink) and 20 Mbps (uplink) data rate using pulse position modulation scheme at 1550 nm wavelength.	[20]
European Data Relay System (EDRS)	Communication	This is a joint research program between European Space Agency (ESA), Airbus Defense & Space and the European Commission for inter-satellite laser communication. They demonstrated a laser transmission at 1.8 Gbps from European Sentinel-1A (in LEO orbit) to Alphasat (in GEO orbit).	[28]
Free Space Quantum Key Distribution (QKD)	Communication	This research demonstrated the feasibility of QKD between ground-to-ground /air-to-ground in establishing secure key exchange at 7.9 bps for 20 km air-to-ground link and at 12.8 bps for 144 km ground-to-ground link.	[29]–[31]
China Quantum Science Satellite (QSS) Program	Communication	This program includes series of satellite launch until 2030 that delivers secure quantum information for various military missions, exploring dark matter, cosmic radiations, etc. For secure communication, cryptographic keys are generated, with a pair of entangled photons, produced by the usage of crystals.	[32]
Defense Meteorological Satellite Program (DMSP)-5D3	Meteorology	This is a 1960s joint program operated by the US Air Force Space Command and the National National Oceanic and Atmospheric Administration (NOAA) to provide meteorological, oceanographic and solar-geophysical data, which can be relayed to deploy forces for improved tactical operations. DMSP-5D3 is the eleventh and the latest version of the military meteorological satellites which includes a lot of instruments, along with laser threat warning sensors, improved microwave imager sensors and extended space weather sensors, etc.	[33], [34]
Blue Beam Project	Imagery	This is an operation of the National Aeronautics and Space Administration (NASA) to project holograms from space on to the ground, in the sky, or on the ocean for special deceptive missions. The system consists of space-based laser projectors or relay satellites that would pass the data to the piloted vehicle or aircraft to produce holographic images for battlefield intelligence.	[35]
DARPA's Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) program	Military warship	This project is also known as "Sea Hunter" is undergoing open-water testing. It is capable of identifying and tracking diesel submarines using electro-optical/IR/laser sensors or non-radar active technologies.	[36]
Boeing High-Energy Laser Mobile Demonstrator (HEL-MD)	Military weapon	This US military project aims to track and destroy aerial targets like drones, missiles, rockets, etc., from ground-based vehicles. Demonstration of high-energy laser (HEL) weapons in maritime environment was carried out using 10 kW solid state laser at IR wavelength.	[37]
Robust Electric Laser Initiative (RELI)	Military weapon	This is a joint project operated by the department of Defense (DoD), Lockheed Martin, Northrop Grumman and Boeing for developing high-energy advanced electric laser technology for tactical operations. Their aim is to produce 100 kW laser while they have successfully demonstrated 30 kW laser power in 2013.	[38]
Solid-State Laser Technology Maturation Program	Military weapon	This program is operated by the office of Navy research (ONR), whose aim is to provide mature HEL weapons for future military operations.	[39]
Aero-Adaptive/Aero-Optic Beam Control Program	Military weapon	The is a joint program of DARPA and AFRL whose objective is to deploy HELs on arm aircraft that are able to fire in any direction. The first demonstration was successfully validated in 2015, when a laser beam was fired at jet speed in all directions.	[40]
Future programs			
Long Range Research & Development Program Plan (LRRDPP)	Space, air and underwater technology	This program will focus on emerging technologies for space, air and underwater, to enhance the future war-fighting capabilities of military in 2025 to 2030 time frame.	[41]
Project Dragonfly	Interstellar travel	This project aims to study the feasibility of interstellar travel using laser-propelled inter-stellar probe.	[42]
Extreme Universe Space Observatory (EUSO)	Space debris clearing	This project, planned for 2018, will intent to deploy lasers on international space station for clearing off space debris.	[43]
Quantum Experiments at Space Scale (QUESS)	Communication	After the successful launch of quantum satellite by the Chinese Academy of Science, in 2016, China is now planning for European-Asian quantum-encrypted network by 2020 and a global network by 2030. This will allow a secure quantum cloud computing for tactical military operations.	[44]

choice of wavelength depends upon transmission window for atmospheric or underwater links. While underwater links have a good transmittance in the blue-green region i.e., in the region of 0.42 to 0.52 μm for clear water conditions, on the other hand, free space optical links operate in near IR and visible spectrum between 0.75 μm to 1.6 μm. Further, in order to facilitate challenging battlefield environments that may include diverse terrain (desert, urban, mountain, water body) or signal congestion/ denial, ultraviolet spectrum is the viable option to establish non-line-of-sight (NLOS) laser link. NLOS or beyond-LOS (BLOS) links are generally used as command and control links that require low data rates as compared to LOS links that require high data rates for ISR. Lasers, when used as sensors in applications involving target or range detection for moving or static platforms, require the compatibility of sensors processing algorithm with the resolution of laser sensor. These applications usually involve pulsed laser of high or moderate energy to provide more accurate information for tactical operations. The choice of wavelengths in such cases has to be done very carefully to retain the covertness desired in military operations. Furthermore, lasers greater than 1 kW power are used as high-energy laser (HEL) weapons or blind sensors to cause structural damage to any specific target. These high-energy weapons can be either continuous lasers or pulsed lasers designed to convert the laser optical energy to thermal energy, that causes physical destruction against intended targets. Table II gives the description of lasers used for various military applications.

The following subsections discuss the military usage of laser technology which can be classified into four major areas: (i) laser range-finders (LRF) and laser target designators (LTD), (ii) laser remote sensing, including laser radars/laser detection and ranging (LADAR)/light detection and ranging (LIDAR), (iii) laser communication systems and (iv) laser guided weapons (LGW).

A. Lasers Range-Finders and Target Designators

In the battlefield environment, the timelines between identifying, tracking and shooting are very critical to ensure the continued success of the warfighters. This requires improved pointing, targeting and designating capabilities during military operations. Laser range-finders and target designators use high-resolution scanning or staring techniques to determine the distance and speed from an object that is located beyond the point-blank range. These devices are traditionally used for 3-dimensional (3D) vision control, positioning or level control. LRF uses time-of-flight principle for measuring to-and-from travel time between the transmitter and the target. They can provide a measuring range, from few meters up to tens of kilometers. These lasers emit short pulses of about 10 ns duration with low pulse repetition rate, say 1-20 Hz, using optical wavelengths that give a low atmospheric transmission loss. This equipment is generally incorporated with thermal equalizers and cooling systems considering a wide range of temperature in the battlefield environment. Fig. 1 shows the block diagram of LRF.

Most of the LRFs and LTDs currently in use are based on Nd:YAG that emits short coded pulses at 1.06 μm wavelength.

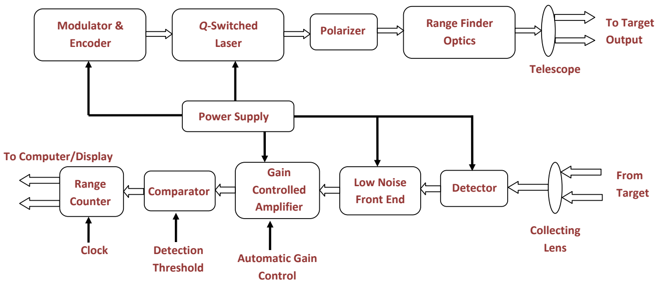

Figure 1: Architecture of LRF

The reflected and scattered target's light is captured by an OE system installed on the weapon that computes the necessary flight path corrections and sends back the control signal to focus the weapon on the target. The pulses are encoded to reduce the risk of jamming or spoofing. The advantage of using solid state lasers is that their power levels can be increased substantially when Q-switching is used to achieve short pulse lengths. These lasers can be frequency-doubled to bring the laser beam into the visible range i.e., 0.532 μm (green), or further divided three or four times down to bring the laser spectra from near IR to ultraviolet (UV) region. Also, the optical beam from Nd:YAG laser is not visible to a naked human eye. A designator designed by Lockheed Martin i.e, low altitude navigation and targeting Infrared for night (LANTIRN) [45] emits short pulses of high peak power, up to 10 MW, is used by US Air Force for variety of tactical applications. Besides providing precise range information to be manned or unmanned military vehicles, these modules also find its application in navigation, 3D object recognition and modeling. Thriving to protect the soldier's eye in a battlefield, lasers with a wavelength greater than 1.4 μm is preferred as these radiations are absorbed in the cornea of the eye and consequently, cannot reach sensitive retina. Therefore, eye-safe laser such as Er:glass solid state laser, operating at 1.5 μm or CO_2 operating at 10.6 μm with a pulse energy less than 10 mJ are a preferred choice for day or night-time operations [46]. The LRFs that use CO_2 lasers have better penetration in adverse conditions and are relatively eye-safe compared to Nd:YAG lasers. Other eye-safe lasers are Raman-shifted Nd:YAG lasers and Er:fiber lasers whose operating wavelength is in the range of 1.53 to 1.55 μm.

Laser designators give the precise marking of ground-based or airborne targets especially for small-sized and well-defended targets. The principle of designation requires the target to be illuminated by the laser beam, either by ground forces or by a gunner on the fighter plane. The reflected light from the target is captured by the host platform or weapon system that allows the automatic tracking of the signal to provide accurate target information to the aircraft, navigation or weapon aiming system. Fig. 2 demonstrates the concept of LTDs in combination with a laser-seeking missile that looks for the reflected laser beam from the target and destroys it . Unless the enemy has abundance of laser warning detectors, it would be difficult to tell who is being targeted.

Precision accuracy depends upon target size, laser beam

Table II: Characteristics of lasers used for various military operations

Laser Type	Wavelength	Purpose	Output	Power
Neodymium-doped Yttrium Aluminum Garnet (Nd:YAG)	1.06 μm	LRF/LTD	Pulsed	0.5-1000 W
Carbon dioxide (CO_2)	10.59 μm / 11.17 μm (Far IR)	Long range LADAR	CW/Pulsed	4 kW to 5 kW peak
Nd:YAG crystal	1.06 μm	LADAR	Q-switched /Pulsed	0.5-1000 W
Raman-shifted Nd:YAG	1.54 μm -1.55 μm	LIDAR	Pulsed	> 10 W
Gallium-Arsenide (GaAs)	0.85 μm	LADAR	CW/Pulsed	> 10 W
Tunable laser Titanium Sapphire (Ti:S)	0.66 μm - 1.18 μm	Atmospheric Communication	CW	0.1-few Watts
Nd:YAG	1.06 μm/0.532 μm	Atmospheric Communication	Q-switched /CW/Pulsed	0.5-1000 W
Helium Cadmium lasers (He-Cd)	0.4416 μm	Underwater Communication	CW	10's of mW
Argon laser	0.5145 μm (green) and 0.488 μm (blue)	Underwater Communication	CW	0.1-few Watts
CO_2	9 μm - 12 μm	Weapon	CW/Pulsed	>100 kW
Deuterium Fluoride (DF)	3 μm - 4.2 μm	Weapon	CW/Pulsed	0.01-100 MW
Hydrogen Fluoride (HF)	2.6 μm - 3 μm	Weapon	CW/Pulsed	up to 150 MW
Krypton Fluoride (KrF) (excimer)	0.249 μm	Weapon	Pulsed	hundreds of Watts
Fiber laser	Variable	Weapon	CW	up to 10's of kW
Indium Gallium Arsenide (InGaAs)	1.55 μm	Illuminator	Pulsed	up to few Watts
Gallium-Arsenide (GaAs)	0.83 μm	Illuminator	Pulsed	up to few Watts
Nd: YAG	1.064 μm	Illuminator	Pulsed	up to 10's of Watts
Vertical-Cavity Surface-Emitting Lasers (VCSELs)	1.064 μm	Illuminator	CW	few mW to 150 kW
Nd: YAG	1.06 μm	Sensor	CW/Pulsed	up to 10's of Watt

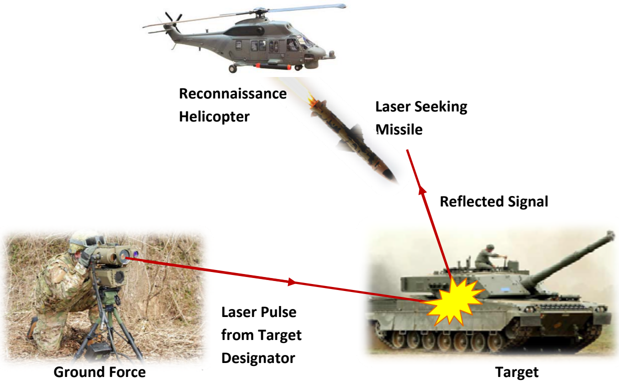

Figure 2: LTD used in combination with laser seeking missile

divergence and designation range. In order to improve the accuracy of LTDs, laser beam divergence has to be chosen very carefully so as to avoid beam divergence losses along the path, between the laser source and the target. A typical example is Thomson convertible laser designation pod (CLPD) equipped with TV and IR camera. The CLPD, when integrated with TORNADO or Typhoon aircraft, provides laser guided bombs a self-designation capability. These designators pods are also integrated with AM-X aircraft [47] and Euro-fighter Typhoon [48] to enhance military capabilities in the battlefield. Similarly, enhanced PAVE WAY II and III [49] use global positioning system (GPS) information to designate any static or mobile target in all weather conditions. This equipment was used during Iraq operations in 2003. The ground laser target designator (GLTD) II and III [50] are equipped with robust and reliable tactical lasers, used by special forces, joint terminal attack controllers and forward air controllers for Afghanistan and Iraq operations.

Joint LTD is a technique to employ two or more laser designators, using the same code from different locations to designate a single target for a single LGW [51]. This technique is usually employed for high priority and time-sensitive targets where LGW locks and tracks the designator with the strongest reflected energy.

B. *Laser Remote Sensing*

Laser radar or LADAR (name adopted by National Institutes of Standards and Technology (NIST)) or LIDAR (name adopted by U.S. DoD) is an active EO remote sensing technique (3D imaging and mapping) which works on the same principle as the radar i.e., project a laser beam (pulsed or continuous) over the required field-of-interest and process the reflected or scattered signal to determine the distance, using the principle of time-of-flight. As compared to traditional

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RF radar, laser radar provides enhanced accuracy in range measurement, velocity and angular displacement. In addition, the material composition of the target can also be determined by measuring certain properties of the reflected light, such as Doppler shift. LIDAR is generally used for soft targets like chemical or gas detection whereas LADAR is used for hard targets. These EO systems can be classified according to the type of detection technique, modulation/demodulation technique, laser operating wavelength, interferometer (in coherent laser radar), data collected, measurements to be performed, etc. The technology advancement has led to the development of sophisticated EO systems with enhanced accuracy and increased sensitivity to back-scatter light. The classification of laser remote sensing devices is shown in Fig. 3.

These laser remote sensing devices are used for various applications, such as 3D terrain mapping, battle damage identification (BDI)/battle damage assessment (BDA) in real time, improved mission planning from 3D mapping, detecting and sensing chemical agents, airborne laser mine detection system (ALMDS) for counter-mine warfare, unmanned vehicles navigation and guidance, etc. Depending upon the application requirements, a variety of lasers (such as Nd: YAG $(1.06\ \mu m)$, Raman shifted Nd: YAG (1.54 μm), frequency shifted Nd: YAG (0.53 μm), Er: YAG (2 μm), CO_2 (9.2 μm - 11.2 μm) and GaAlAs (0.8 μm - 0.904 μm)) with varying power, pulse width and modulation techniques are used. The distance that can be sensed by these devices depends upon the peak power, beam divergence, atmospheric losses, target reflectivity and detector sensitivity. It has to be mentioned here that active EO systems may not always be advantageous over conventional radar systems. The conventional radar are operational in all weather conditions (except for very heavy rains), have lower life-cycle cost, requires no eye safety regulations and are stealthier than the active EO sensing devices.

Various organizations including DARPA are working towards the enhancement of military radar with high bandwidth, high resolution and long range laser radar. The speed, accuracy and resolution of these systems depend upon the length of the laser pulse and for this reason, there is a lot of ongoing research to produce pulses at femtosecond intervals or even less [52]. This will help to provide accurate timing information to perform absolute ranging at long distance. The use of artificial intelligent in laser radar will further facilitate the target selection process and enable quick decision-making in rapidly changing electronic war-fight [53]–[55]. The use of differential absorption laser radar (DIAL) in military helps to determine the properties of a remote location by processing certain characteristics (amplitude, frequency, polarization) of back-scattered light. With the advent of chemicals and biological weapons, DIAL system is very beneficial for space-based remote sensing applications to detect a wide variety of chemical compounds, present in the air, that would explode during any military operation. DIAL systems operating in UV spectra not only identify aerosol backscatter but also detect Rayleigh backscatter signal. These DIAL systems are currently used by NASA for testing effluent levels present in stratospheric and tropospheric layers of the atmosphere. Space-based DIAL system provides a remote assessment of battlefields to sense various biological or chemical agents present in the atmosphere, immediately after the attack. These systems require high power tunable lasers to detect the back-scatted signal that is likely to be weak in strength. The space-based LIDAR system is a good example of a long-range biological stand-off detection system (LR-BSDS) [56]. Developed by Schwartz Electro-optic, this system uses diode-pumped solid state laser for sensing bio-aerosol clouds in case of biological warfare attack. Environmental remote sensing is carried out to investigate certain physical properties of the region or the space to provide a way of aiding target recognition. This helps measurement and signature intelligence (MASINT) mission by gathering distinctive signatures of fixed or dynamic targets and hence, providing new dimensions to intelligence during war scenarios. For example, the texture of the target affects the state of polarization of the reflected beam and helps in target identification. Similarly, the degree of reflectivity determines the atmosphere's humidity and provides advanced information to adjust the weapon systems to hit the target. Other space-based LIDAR systems are studied in [57]–[60]. An integrated tactical warning and attack assessment concept were proposed in [61] to link up the data from multiple sensor systems for providing near-real-time warning of missile, air and space attack. It would also help in accurate estimation of theater missile trajectory or to improve the capability of negating the target before launch, or in the boost phase, by integrating data from multiple sensor units.

Laser-induced breakdown spectroscopy (LIBS) using UV and near-IR lasers are also used in military applications for explosives' detection, chemical or biological agents warfare usage. LIBS can be applied to a variety of materials including plastics, organic compounds, biological material and other hazardous substances. Its recent advances are studied in [6]. Various other remote detection techniques namely, photo-acoustic spectroscopy, stand-off terahertz spectroscopy, terahertz-induced fluorescence, laser-induced vapor emission, fluorescence spectroscopy and differential scattering (DISC) are also used for tactical warfare. In case of real time scenarios requiring a quick response for bio-fluorescence detection and identification, UV light spectroscopy [62] is used. UV light source and a high gain photo-detector are used by these devices in order to detect weak optical signals [63]. Due to high internal gain and low noise characteristics, photo-multiplier tubes (PMTs) or UV-sensitive avalanche photo-diodes (APDs) are good choices as photo-detectors.

Further, surface-enhanced Raman scattering (SERS) is used for advanced remote sensing and identification of various chemical agents and explosive threats present in the atmosphere. This is a highly sensitive and powerful vibrational spectroscopy technique that provides structural detection of molecules in very low concentrations, through the amplification of electromagnetic fields generated by the excitation of localized surface plasmons. SERS-based techniques, in conjunction with molecularly imprinted polymers, (MIPs) provides a high level of sensitivity for explosive detection [64]. More details on SERS technique and its

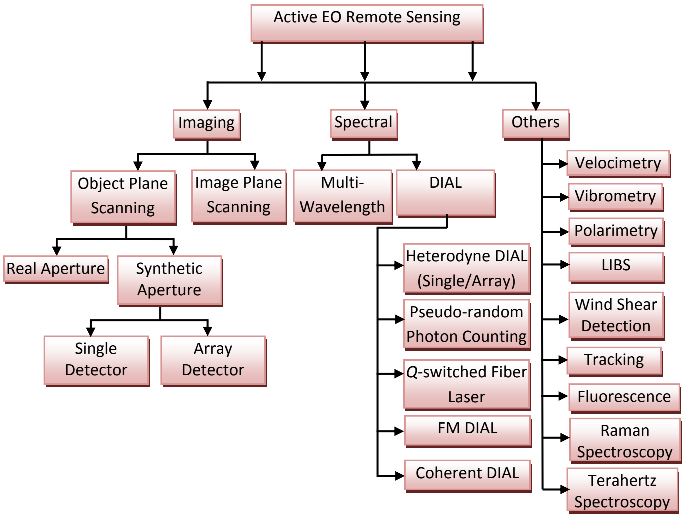

Figure 3: Classification of laser remote sensing

future perspectives are presented in [65]–[67]. Other advanced SERS-based techniques, such as UV SERS [68], tip enhanced Raman spectroscopy (TERS) [69] and SERS integration with ultra-fast spectroscopy [70] are currently under research for defense applications.

C. Laser Communication Systems

With the upcoming trend of electronic warfare, military operations demand broadband capacity with the highest level of security. Nowadays, tactical operations are enabled with large volumes of ISR imagery and video data that are being transferred from sensing locations to battlefield grounds. Also, timely access to critical information delivered to soldiers in the battlefield can change the war game. For this reason, laser communication, also known as free space optics (FSO), is a good choice owing to its high carrier frequency, ultra-low latency and immunity towards EM radiation. These links allow LOS communication between two parties to have a very low probability of detection, interception or exploitation (LPD/LPI/LPE). LPD means preventing the enemy from detecting the transmission whereas LPI is preventing an enemy from tapping on to the information. LPE is concerned with the prevention of exploitation of signals caused by spoofing, sniffing, decoding or position monitoring. Exploitation involves using the transmitted data for intelligence or counter-intelligence purposes. The covert nature of this technology makes the laser beam resilient to jamming or spoofing, which is essential for military operations.

The probability of laser beam being detected depends upon the beam divergence and spectrum of frequencies emitted by the laser. Covert military operations demand to work in near the IR band, with narrow beam divergence and minimal spillover, or spurious emissions, like side lobes. Laser beams can still be detected using appropriate tools like IR goggles. Since the spectral sensitivity of these goggles is from 0.4 μm to 1.3 μm, it enables the soldiers to see both visible (0.4 μm to 0.7 μm) and near-IR light (0.7 μm to 1.5 μm) through these goggles. Further, environmental conditions like smoky wartime scenario, fog, haze and dust particles, scatter the light and make the laser beam detectable. In such cases, in order to minimize the probability of detection, transmitters should not use excessive power; it would minimize the scattered light and reduces detection probability.

Intercepting a laser beam requires tapping the information signal by using some sensing device in the path of the transmitted signal. It is almost difficult to intercept a laser transmission without disrupting the system, owing to the narrow divergence of the optical beam. As most of the signal falls within the detector surface area, intercepting the signal blocks the transmission path resulting in a significant drop in the received power level and therefore, raising an alarm for *intrusion detection*. Consequently, for security reasons, a beam with narrow beam divergence is preferred, although it causes difficulty in pointing and aligning the beam with a distant receiver. To resolve this, blockage shields helps to minimize the probability of interception. Fig. 4 shows various scenarios of transmitter's laser signal interception.

Besides LOS communication, NLOS EO laser communication utilizing UV radiation is also studied for military applications [71]. With the development of UV light emitting diodes (LEDs) and APDs, short-range NLOS UV communications offer significant advantages over LOS links, by relaxing, pointing and tracking requirements of IR links. Therefore, laser technology is a good alternative to traditional RF links as it is capable of providing secure, high capacity and rapid information transfer for dynamic mission planning. Due to its reasonable SWaP advantages, laser technology is very beneficial for space applications. Laser communication links can be applied to both static and mobile platforms for ground, air or underwater environments. Despite the many benefits of laser communications, this technology has considerable limitations, that prevent it from being a direct replacement for conventional RF communication. The performance of laser links is very susceptible to varying weather conditions and

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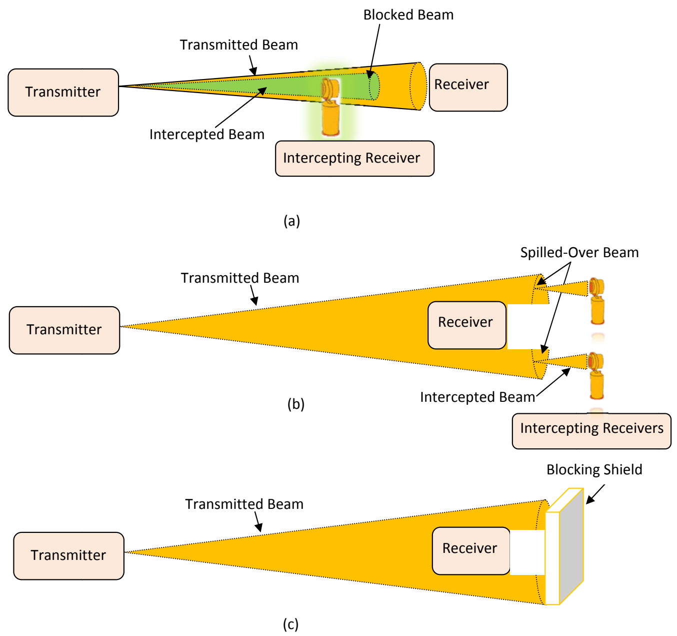

Figure 4: Various scenarios for intercepting a laser beam: (a) intercepting receiver placed between intended transmitter and receiver, (b) intercepting receiver placed behind the receiver to capture some of the beam spillage due to beam divergence and (c) blocking shield placed behind the receiver to lower the probability of interception

it deteriorates during heavy fog, smog or high temperature circumstances. For this reason, military bodies around the world are looking at the laser communication as a technology to augment the existing RF-based system or keep it handy to provide assistance in case of jamming. Laser communication systems are generally designed for short-range point-to-point or multi-point configurations, where other communication networks are practically impossible to be installed.

Various developments in laser communication have been observed by many defense organizations over the past few decades. In order to support both commercial and DoD requirements, various experimental investigations have been carried out for terrestrial lasercom links, space laser links, air-to-ground/ground-to-air laser links, air-to-ocean/ocean-to-air laser links, as presented in Fig. 5 and Table III. These developments have demonstrated increased throughput capabilities with low probability of interception for future electronic warfare scenarios.

In 2013, Exelis Inc., and Innovative Technology Solutions Inc., commonly known as NovaSol, have successfully demonstrated a duplex transmission of high-resolution images and video up to 100 Mbps, over a distance of 30 miles [27]. Air-to-ground optical links up to multi-Gbps were effectively validated by MIT Lincoln Laboratory [72]. The system incorporated coding, interleaving and spatial diversity techniques in order to improve the availability of the link for all weather conditions.

The DARPA's FOENEX program headed by Applied Physics Laboratory (APL) of the Johns Hopkins University has been successfully field-tested for communication between ground and a moving aircraft at various ranges from 30 km to approximately 75 km and between two aircraft ranging up to 160 km [73]. Another project, jointly carried out by AFRL and Exelis Inc., was 'fast airborne laser communications optical node (FALCON)' [74]. This project established 2.5 Gbps full duplex link between two aircraft at a distance of 130 km. In case of air-to-air or air-to-ground communications, the relative motion between the two platforms, i.e., Doppler effect has to be accounted for using acquisition, pointing and tracking subsystems.

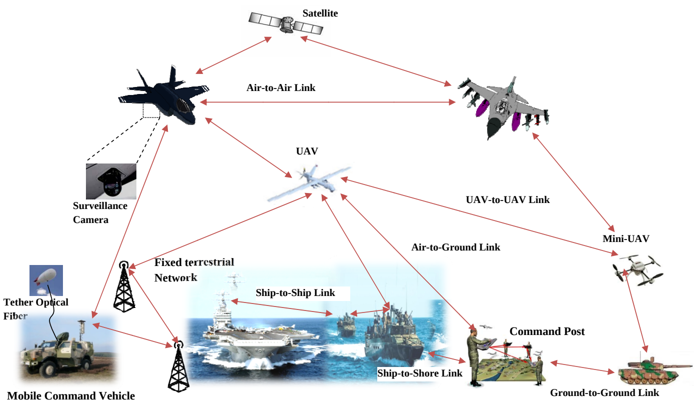

Figure 5: Various scenarios for laser communication links

Space-based laser communications have observed sufficient amount of developments over the last few years. The first DLR experiment was carried out in 2007 between NFIRE, a LEO experimental satellite and TerraSAR-X, a German commercial synthetic aperture radar (SAR) satellite using Tesat spacecom's laser communication terminal (LCT). In 2013, European communication satellite Alphasat I-XL, in geostationary orbit, utilized LCT to demonstrate wide-band communication possibilities with European Earth observation satellite, Sentinel 1A, in near-Earth polar orbit. The LCTs on Alphasat and Sentinel 1A transmit data (up to 1.8 Gbps) across a distance of 45,000 km. Later in 2016, the Eutelsat 9B, a commercial telecommunication GEO satellite, hosted LCT as a data relay payload for EDRS. After an efficacious demonstration of inter-satellite laser communication (up to 5.65 Gbps), Tesat-Spacecom is currently incorporating the system in EDRS program, allowing aircraft and drones to transmit real time high-resolution pictures and videos during electronic warfare [75].

The ONR's blue-green naval science and technology project is working towards exploring various aspects of maneuvering electromagnetic spectrum for electronic warfare, surveillance and communications. They are working towards globalized communication and network architecture using EO sensing devices, high-energy and ultra-short pulse lasers for efficient operations in highly dynamic electronic warfare environment [76]. John Hopkins's APL and AOptix also demonstrated multi-Gbps wavelength division multiplexed (WDM) lasercom link over a long range of 150 km [77]. This experiment observed significant received-power variations, link outages and data loss due to atmospheric fades. Since the performance

Table III: Demonstration of laser technology for various military applications

Project	**Purpose**	**Year**
Tactical Airborne Laser Communications (TALC) program- DARPA	Duplex communication between aircraft and a submerged submarine	1989-1991
Modulating Retro-reflector Lasercom Systems- NRL	Retro-reflecting systems for military applications	1998-present
Fast Airborne Laser Communications Optical Node (FALCON)- AFRL	Airborne communication at 2.5 Gbps	2003-2010
Maritime Free Space Lasercom Test Facility- NRL	Maritime lasercom link at 2.5 Gbps for a distance of 32.4 km	2004-2007
European Data Relay Satellite System (EDRS)	Laser space communication systems	2007-present
Dynamic Tactical Communications Networks (DTCN)- ONR	Autoconfigurtion and adaptive traffic management for tactical missions	2009-2013
Free space Optical Experimental Network Experiment (FOENEX)	Air-to-ground and hybrid optical/RF four node networking at up to 10.3 Gbps	2010-2012
Tactical Relay Information Network (TRITON) program-DARPA	Submarine laser communication with airborne systems	2010-2013
Tactical Line-of-Sight Optical Network (TALON)- ONR	Maritime free space optical communication systems	2010-2015
Airborne Network using Spectrum-Efficient Communications Technologies (ANSECT)- SBIR*	Airborne battle-space communications	2010-present
GlobeNet- EDRS extension program	Laser space communication systems	2015-present
Communications and Inter-operability for Integrated Fires (CIIF)	Enhancing throughput and scalability data distribution system for air and missile defense	2017 onwards
Research, Development, Test and Evaluation (RDTE) program - Communication Technology	Focus on vehicular and airborne platforms, co-site interference, new mobile networking protocols, etc.	2017 onwards

*SBIR: Small Business Innovative Research

*DLR: German Aerospace Center (abbreviated as Deutsches Zentrum für Luft- und Raumfahrt)

of laser communication is highly dependent on atmospheric factors, it was observed that hybrid RF/optical approach would enable high capacity and all weather communication capability. Therefore, various technological developments were carried out to demonstrate the feasibility of integrated RF and optical links, such as DARPA's optical/RF combined adjunct (ORCA) program [78], AFRL's integrated RF/Optical networked tactical targeting (IRON-T2) program [79] and DARPA's FOENEX program [80].

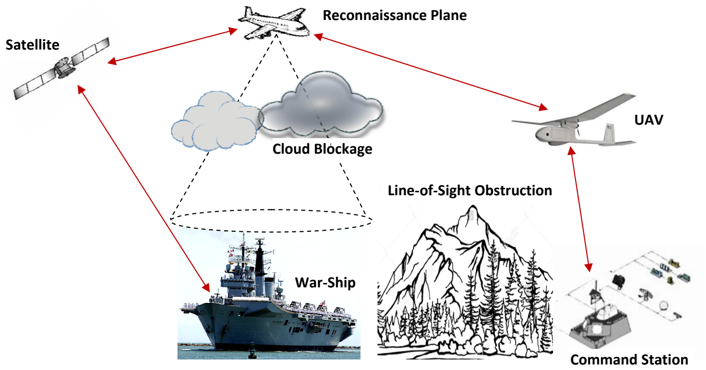

Figure 6: Spatial diversity illustration for military laser communication

In [81], a hybrid RF/optical network has demonstrated its capability of providing point-to-multi-point 10 Gbps link over a distance greater than 200 km. Various other methods are adopted to dynamically normalize the received power variations due to channel fading such as using adaptive optics, optical modems and automated gain control systems. TALON developed by NRL is incorporating optimized tracking and robust modem technologies in order to reduce the weather's impact on the system's performance [82]. AOptix technology developed curvature mode adaptive optics for airborne systems to cope up with turbulent atmospheric conditions [83]. They demonstrated unique pointing, acquisition and tracking (PAT) capabilities using lasercom terminal mounted on an inertially stabilized gimbal. The system demonstrated real-time communications with pointing accuracy of fewer than 100 μrads. The use of tunable lasers, non-linear optical materials, multi-line emission lasers, aperture averaging, time diversity, forward error correction (FEC)/automatic repeat request (ARQ) or spatial diversity also help in mitigating the adverse effects of the atmosphere. Fig. 6 gives the illustration of spatial diversity which provides alternate routes for communication if any link is blocked due to some natural or atmospheric factors.

Nowadays, with the development of quantum physics, military organizations are carrying out a lot of research in quantum cryptography communications. This technology can bring fundamental changes in military capabilities and many countries, including China, US, Germany, Sweden and Japan, are investing substantial funds into this field. Quantum cryptography utilizes some specific properties of the quantum state of light to generate secret cryptographic keys for a secure communication. The security of the transmission relies on the principle of quantum mechanics and Heisenberg's uncertainty principle that prevents the information from being tapped or intercepted. The secret random keys are only known within two geographically separated parties for encryption and decryption of messages. This prevents illegal third party listeners or intruders to intercept or eavesdrop the quantum transmission. The secure generation of these keys is possible using QKD. The QKD is developed from quantum conjugate code, which was

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proposed by Stephen Wiesnerin, in the late 1960s [84]. These codes led to the generation of cryptographic systems, which are based on the quantum mechanics' principle. The first quantum key distribution protocol was published in 1984 and is now known as "BB84 [85]. Its first experimental demonstration was carried out using polarized photons, up to a distance of 30 cm. Over a period of time, several other research groups have carried out experimentations for optical fiber-based QKD systems, and free space QKD for satellite-to-satellite/ground-to-satellite/deep space communication systems [86]–[91].

D. Laser Weapons

Laser weapons are efficient and powerful countermeasure utilities against any form of external threat, including ground-based or space-based military menaces. They offer several advantages over conventional weapons systems. Since laser beams travel at the speed of light, it provides near-real-time transfer of information to the soldiers immediately after target detection. The coherence of laser beams provides a highly focused energy which causes physical destruction to the structures, by converting laser energy thermal energy. Since these devices are constantly powered or reloaded by chemical/electricity energy storage, they have the capacity to engage multiple targets with fewer moving mechanical parts. Lasers weapons provide promising and cost-effective solutions for tactical missions, unlike conventional ballistic missiles. The incremental cost per shot for ballistic missiles is essentially the cost of the ammunition expended, whereas, on the other hand, laser weapons expend only energy. Here, the cost per shot equals the cost of the chemical fuel or the fuel required to generate the electricity, which is much less as compared to conventional weapons. Also, these directed energy weapons provide exceptional precision striking accuracy, that results with little collateral damage and allows the use of lasers for lethal or non-lethal applications. Fig. 7 demonstrates the applications of laser weapons for ground, space and maritime environments.


Air-to-Ground
Ground-to-Air
Ship-to-Air
Ship-to-Ship

Figure 7: Laser weapons for ground, space and maritime applications [92]–[95]

Laser weapons are classified on the basis of their energy/power levels: high, medium or low energy weapons. Some experts also classify laser weapons according to their operational impact as shown in Fig. 8. They are distinguished into three broad areas ranging from jamming of sensors to the destruction of optoelectronic devices and ultimately destruction of the complete mechanical structure. Low energy lasers usually give less than 1 kW of power and are used in weapon simulation systems for training or for jamming the sensors in communication systems or can be used in anti-personal mode against the human eye. The use of these laser weapons for future military tactical operations will radically change the battlefields' situation; these lasers are more silent and less detectable for the enemy to guard against them. Medium energy lasers produce 10 kW to 100 kW of power and are used for the destruction of optical or optoelectronics devices on ground or space-based targets. High-energy lasers (HEL) generate greater than 100 kW of power and are used for anti-aircraft or anti-missile systems. Having the speed of light, these lasers provide short engagement time for the target, depending upon terrain and speed of the target. Many countries like US, Russia, China, Europe, India and Germany are carrying out extensive research on HEL for navy or air defense purposes. HEL, due to high costs and bulkier structure, will probably be limited to the protection of costly high-technology targets such as air and navy bases, high-level command posts and aircraft carriers.

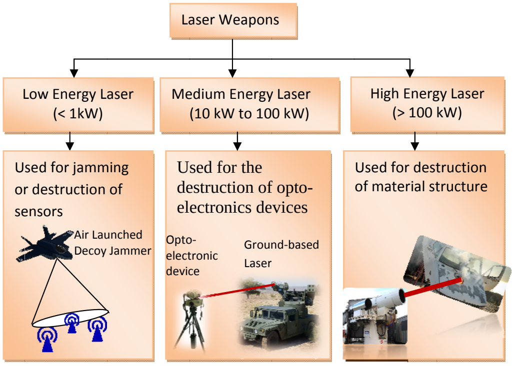

Figure 8: Classification of laser weapons

As previously discussed, when capable of generating higher power levels, ranging from kilo-Watts to Mega-Watts, any laser can be used as a laser weapon. However, these lasers have special needs for its efficient operations i.e., cooling requirements, laser fuel storage requirements, environment & personal safety requirements, pointing and tracking requirements. The cooling requirement is essential for these lasers to compensate for the huge amount of heat generated while firing the laser beam. If cooling arrangements are not properly made, the heat in the atmosphere will make the laser beam wider, increasing the difficulty to align it with the target. These weapons require adequate fuel supply or electricity energy stores to allow multiple target engagements simultaneously. Laser weapons have to abide by the protocol on blinding laser weapons which prohibits the use of lasers specifically designed for blinding personnel.

Laser weapons can be either ground-based or space-based as depicted in Fig. 9. Ground-based laser weapons utilize multiple relay mirrors in space so as to destroy a theater ballistic missile. These relay mirrors are used to extend the range of high-energy laser weapons, as it compensates for the limiting factors caused due to atmospheric absorption, turbulence and curvature of the Earth. A high-energy laser beam from a ground station is relayed to a missile with the help of these mirrors. Since the beam has to pass through the atmosphere to reach the constellation of relay mirrors in space, the energy requirement of ground-based lasers is substantially larger than space-based lasers, owing to greater losses due to atmospheric transmission, thermal blooming and larger distances. The use of bifocal relay mirrors effectively puts the laser source at the mirror. This increases the intensity on the target at a specific range or extends the range of the laser, up to the target while retaining the original brightness or intensity. These lasers have evolved during the strategic defense initiative (SDI) era but have not received significant emphasis due to the variety of technical challenges involved with its design and development [96].

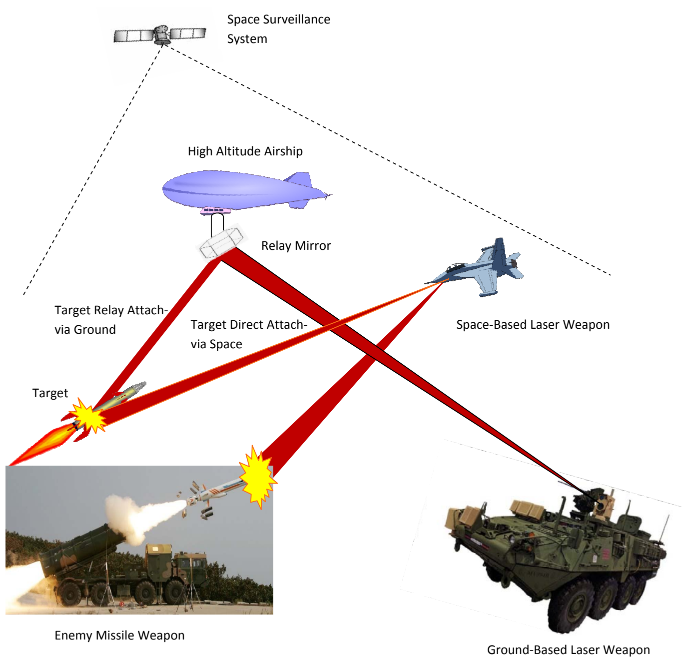

Figure 9: Demonstration of ground-based and space-based laser weapon

Ground lasers are equipped with beam control and adaptive optics (AO) systems to compensate for atmospheric distortion and focus the laser beam onto the target. Space-based laser weapon systems cover larger theaters of operation compared to ground-based laser. However, these lasers require recharging and refueling of laser weapons' chemicals placed on-board in space. The laser weapon system, whether it is ground-based or space-based, requires high power laser, beam control system and highly accurate PAT, to direct the laser beam onto the target. Adaptive optics, which are a critical part of the beam control system, senses the turbulence in the atmosphere and pre-compensates the outgoing optical beam, in order to improve the system capability. It comprises of high-speed processors, deformable mirrors and high-speed optical sensors that help to correct the distorted wavefront and align the high-intensity laser beam, focusing directly on to the target. These weapons use low power beacon beam for acquiring and focusing the distant target before they produce high power beams for destroying the target. Fig. 10 shows the beam control mechanism using adaptive optics used in laser weapons. It makes use of deformable mirrors which are driven by AO control loops that employ wave-front sensor measurements in order to compensate for turbulence-induced distortion of optical beams, propagating through the atmosphere. Before sending a high-energy laser beam towards the target, the reflections from beacon created by illuminating the target with low energy laser signal is used to determine the commands to the deformable mirror.

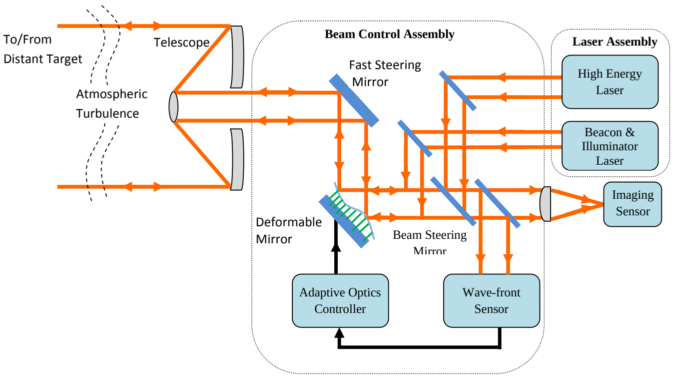

Figure 10: Demonstration of beam control mechanism using adaptive optics

Mainly five types of lasers are considered as good candidates for laser weapon:

- chemical laser,
- solid state laser,
- free electron laser (FEL),
- fiber laser and
- liquid laser.

Each of these lasers has their own unique characteristics that make them suitable for certain operational applications. Chemical lasers are the most matured laser weapon technology that generates high power from exothermic chemical reactions to strong IR radiation. Popular lasers in this category include Hydrogen Fluoride (HF), Deuterium Fluoride (DF) and chemical oxygen iodine laser (COIL). With the success of the first HF laser, generating 1 kW power in 1965, various military organizations gained interest in producing more powerful lasers (> 100 kW) for tactical missions. These lasers are somewhat bulky as they require a large amount of chemical storage and cooling system for its proper functioning. Various high-energy chemical laser weapons have been demonstrated over the past 45 years including MIRACL, ALPHA and Navy-ARPA chemical laser (NACL). ALPHA HF laser is a small-sized Mega Watt power laser for space applications. Tactical high-energy laser (THEL-DF chemical laser), Mobile THEL (MTHEL-DF chemical laser) and advanced tactical laser (ALT-COIL with beam control) are compact field-ready weapons that have successfully demonstrated their capabilities for shooting down short and medium-range targets. With some modifications to THEL, a deployable ground-based directed energy weapon, known as high-energy laser for rockets, artillery and mortars (HELRAM), is used for short range military threats. Laser equipped aircraft like airborne laser (ABL) [97] is equipped with multiple laser systems: primary laser (COIL) with Mega Watt power for target's destruction, illuminating laser for ISR and high precision laser for target tracking beam control systems. ABL is capable of detecting the missiles shortly after the cloud break and provides real-time launch warning and its location to the rest of the forces. It also provides trajectory information and impact point predictions, shortly after burning out.

Solid state lasers are powered lasers that pass electricity through a crystal, or glass medium, to produce laser beams. In early days, flash lamp pumped solid state lasers were used to achieve population inversion and stimulate a high-quality laser beam up to kW level. The most popular solid state laser is Nd:YAG laser, operating at 1.064 μm, which can operate in both pulsed or CW mode. Eye-safe solid state laser offers significant reduction in SWaP and therefore, is considered as a portable laser weapon. Boeing's HEL-MD is a 10 kW solid state fiber laser around one micron designed to destroy rockets, artillery, mortars and drones (RAMD) from ground-based vehicles [98]. Fiber lasers are more compact and require less power to maintain beam quality than any other HEL designs. Its beam control system comprises of mirrors, high-speed optical sensors, processors and adaptive optics system, to precisely align the beam onto the target in real time. A single mode fiber laser is capable of producing 10 kW of power sufficient to shoot down any missile at an approximated distance of 1.5 km. In order to further achieve the required power levels, multiple fiber lasers can be combined so that a high power overlapped beam, from an individual laser, strikes the target. Fig. 11 shows the incoherent combining of fiber lasers, which is individually controlled by a beam steering mirror, to direct each beam onto the target. Such fiber lasers are highly efficient, robust, compact and require low maintenance that makes them suitably used for tactical energy-directed military applications.

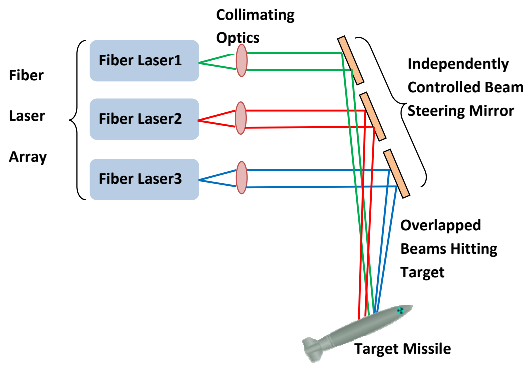

Figure 11: Fiber laser architecture for high power and long range directed energy weapon

The Laser Weapon System (LaWS) is navy defense system which has successfully demonstrated the shoot down of UAV from a HEL weapon deployed on a small ship. The system consists of an array of solid state lasers, generating IR beams at varying output power, in the range from 15 to 50 kW, so as to either warn or damage the designated target. ONR will now extend the experimentation by performing a shipboard test with 150 kW laser weapon system in the near future [99].

The FEL generates high-intensity light beam by utilizing the energy from unbound accelerated high-energy electrons. As a true electric laser, it creates a special interest to the navy and is being considered a good choice for HEL laser weapon for surface shipboard in the 2020 time frame. The tunability of these lasers to different wavelengths provide a dynamic capability of the laser weapon to cope up with changing atmospheric conditions. FEL is capable of generating Mega Watt power and is well suited for multiple naval applications [100].

Another category of laser weapon is the electrically powered fiber laser, which uses optical fiber doped with rare earth elements as a gain medium. Modern fiber lasers are considered as solid state lasers which confirmed to have larger benefits than traditional solid state laser.

The area defense anti-munitions (ADAM) laser system is a 10 kW mobile ground-based fiber laser system developed by Lockheed Martin [101]. This system has proven its worth with small-caliber rockets and maritime targets. Further advancements in laser weapon technology (Lockheed Martin) has resulted in advanced test accelerated laser demonstration initiative (ALADIN) [102], high-energy asset (ATHENA) [103] and aero-adaptive aero-optic beam control (ABC Turret) [104]. ALADIN is a 30 kW fiber laser weapon, developed by spectral beam combination of multiple lasers to improve its efficiency, beam quality and lethality. It approximately utilizes 50% less electricity than conventional solid state laser technologies and is designed to defeat small airborne, UAVs and sea-based targets [105]. The architecture of ATHENA is based on ADAM laser weapon technology and incorporates high-energy 30 kW ALADIN laser. It demonstrated the first successful field testing of an integrated ground-based single-mode fiber laser weapon. ABC Turret is the first laser turret ever developed for supersonic jet-fighter aircraft that utilize spectral beam combining fiber laser to engage enemy aircraft or missiles over 360 degrees coverage capability.

DARPA's Excalibur program consists of optical phase array systems to compensate for the turbulence in the atmosphere and thereby, to increase the laser irradiance at the target, up to 10s of kW. Researches are still on going to extend the power levels up to 100 kW for HEL weapons [106].

RELI is working towards a 100 kW class laser weapon, using spectral combining of laser beams from multiple fibers to produce a single high power beam of sufficient good quality. Another DARPA's program, high-energy liquid laser area defense system (HELLADS) [107], uses the liquid as a lasing medium, containing active chemical species for stimulated laser emission. This program is working towards the development of a 150 kW HEL weapon with a considerable reduction in size and weight that allows easy integration into tactical aircraft like fighters, bomber, tankers and UAVs.

IV. OTHER APPLICATIONS AND FUTURE SCOPE

Lasers are used in numerous other applications, like battlefield illuminator, weather modifier, holographic projectors and power beamers. Laser illuminators are small and light weight devices that provide the finest night vision, to help soldiers to illuminate targets for reconnaissance systems. It also provides improved target acquisition, efficient landing in case of poor light conditions, enhanced night security for sensitive sites and augment infiltration and ex-filtration of special operation teams. Future battles may necessitate space-based battlefield illumination to improve the vision in dark target sites from any given satellite position. This would require a precise pointing system for both satellite and ground site, that is to be illuminated in order to permit a pointing vector calculation for the laser beam. These lasers generally operate in 0.8 $\mu\mathrm{m}$ to 0.9 $\mu\mathrm{m}$ wavelengths for night vision systems and 8 $\mu\mathrm{m}$ to 12 $\mu\mathrm{m}$ (far IR) for forward-looking IR (FLIR) systems.

Another dimension where lasers can improve the military capability in future battlefield operations is its use as weather modifier. Since weather plays a dominant role in military operations, therefore, any ability to control it can bring a significant change in the war scenario. Lasers can be used as weather modifiers by using directed energy sources; they then provide enough energy to the localized region of the atmosphere to change its weather. High Frequency Active Auroral Research Program (HAARP) conducts various experiments, using electromagnetic frequencies to analyze the behavior of ionosphere, in order to enhance military communications and surveillance capabilities for defense purposes [108].

Holography is considered as a future warfare weapon that would provide an efficient way of visualization, using photo-acoustic effects in the air to produce 3D images [109], [110]. This offers an interactive and collaborative environment for military officials, to prioritize their next course of action in battlefields. This technology will generate 3D patterns by overlapping a laser reference beam, that has a smooth phase front, with a laser beam that has been scattered from the object that is to be imaged. Although creating a holographic image is now a mature technology, however building them in an open air uncontrolled warlike scenario is a big challenge. In any war scenario, the army officials can use holographic projectors to present a bulk of information, in a huge shared display manner, in order to improve soldiers performance in the decision making process. Further, the touch surface technology, with interactive modules and embedded features like zooming, panning, rotating, etc., can provide an enriching environment for better decision making in the war scenarios [111]. This idea was explored during the 1991 Persian Gulf War but was not implemented for some technical reasons. Therefore, this technology provides a collaborative and interactive environment, offering a geopolitic and geographic view of an operational area, resulting in a real-time picture of the battlefield scenario. Although this technology is yet not under development, however researchers are still working to understand the capabilities of this technology to improve battlefield intelligence and military planning.

Lasers are also used to beam power up to high-altitude unmanned aircraft to periodically recharge them, in order to stay aloft for longer durations of time. The narrow divergence of the laser beam allows most of the energy to be collected by the swarming unmanned aircraft, to ensure their continuous fly at high altitudes. These unmanned vehicles could provide tactical surveillance, telecommunication relay links or temporary navigation support during war missions. They could also be used to fly guard duty over a military combat area or fly in front of a convoy to warn against an ambush. Power beaming can be carried out using either a ground-based or space-based laser. While many challenges remain in ‘ground-to-space’ or ‘space-to-ground’ power beaming, ‘space-to-space’ power beaming could be less complex and transformational. The space-based laser has lesser power requirements as it has an advantage of avoiding losses due to atmospheric absorption, scattering and turbulence. Laser power beamers are also used for power transfer in space or at remote sites, where other sources of energy are not readily available. This technology is currently in a development stage to support future space missions.

V. CONCLUSIONS

In this paper, we have discussed various prospects of laser technology for tactical military applications. Laser technology addresses the need of today’s battlefield, that require the ability to detect the target at longer distances and exchange massive amount of information in a secure and timely manner. Lasers have revolutionized the warfare in their roles as accessories to high-energy weapons. This technology serves as a power tool to the warfighters when used as battlefield illumination elements, range-finders, target designators, LIDARs, communication systems, power beamers or active remote sensors. Owing to the high frequency of the laser system, these devices provide broadband capacity links with SWaP benefit and have a remarkable angular resolution, which is very critical for tactical lasercom deployment. Besides higher bandwidth, lasercom is used where anti-jam is required or RF spectrum is not available. The use of laser, as directed high-energy weapon, requires sufficient amount of power in Mega Watts to cause substantial damage to the distant target. However, laser weapons are an inherently inefficient method to destroy targets as these weapons -if handled improperly- can cause damage to the target as well as the user. These weapons require sufficient cooling between firing, so they offer certain problems for ground vehicles, especially for hand-held laser weapons. Also, during highly turbulent weather conditions including heavy smoke, dust or humidity, these weapons may deflect from the actual path and can miss the target. The military is still working on many engineering problems, in order to compensate for beam wander due to bad weather conditions or movement of target or motion of platform. Further, these HEL poses a significant threat to sensors or military equipments in the battlefield. These sensors may require a protection mechanism such as laser jamming feature built into the sensor platform to ensure the reliability and integrity of these devices in a hostile electronic warfare environment. Also, quantum computing and cryptography are a game-changing technologies in cyber warfare, possibly safeguarding tactical communication against eavesdroppers. With all of these on-going developments and current state-of-art, laser technology would dominate the battle-space in the near future.

NOMENCLATURE

ABL	Air-Borne Laser
ACTUV	ASW-Continuous Trail Unmanned Vessel
ADAM	Area Defense Anti-Munitions
AFRL	Air Force Research Laboratory
ALMDS	Airborne Laser Mine Detection System
ANSECT	Airborne Network using Spectrum-Efficient Communications Technologies
APDs	Avalanche Photo-Diodes
APL	Applied Physics Laboratory
ARQ	Automatic Repeat Request
ASW	Anti-Submarine Warfare
ATL	Advanced Tactical Laser
BDA	Battle Damage Assessment
BDI	Battle Damage Identification
BLOS	Beyond-Line-of-Sight
CIIF	Communications and Inter-operability for Integrated Fires
CLPD	Convertible Laser Designation Pod
COIL	Chemical Oxygen Iodine Laser
DARPA	Defense Advanced Research Projects Agency
DF	Deuterium Fluoride
DIAL	Differential Absorption Laser Radar
DISC	Differential Scattering
DLR	Deutsches Zentrum fur Luft- und Raumfahrt
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DTCN	Dynamic Tactical Communications Networks
EDRS	European Data Relay System
EMI	Electro-Magnetic Interference
EO	Electro-Optic
ESA	European Space Agency
EUSO	Extreme Universe Space Observatory
FALCON	Fast Airborne Laser Communications Optical Node
FEC	Forward Error Correction
FEL	Free Electron Laser
FEWS	Follow-on Early Warning System
FLIR	Forward Looking Infra-Red
FOENEX	Free space Optical Experimental Network Experiment
FSO	Free Space Optics
GaAs	Gallium Arsenide
GLTD	Ground Laser Target Designator
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HE- MD	High Energy Laser-Mobile Demonstrator
HEL	High Energy Laser
HELLADS	High Energy Liquid Laser Area Defense System
HELRAM	High Energy Laser for Rockets, Artillery and Mortars
HF	Hydrogen Fluoride
InGaAs	Indium Gallium Arsenide
IR	Infra-Red
IRON-T2	Integrated RF/Optical Networked Tactical Targeting
ISR	Intelligence Surveillance and Reconnaissance
JPL	Jet Propulsion Laboratory
KrF	Krypton Fluoride
LADAR	Laser Detection and Ranging
LANTIRN	Low Altitude Navigation and Targeting Infrared for Night
LaWS	Laser Weapon System
LCT	Laser Communication Terminal
LEDs	Light Emitting Diodes
LEO	Low-Earth Orbit
LGW	Laser Guided Weapon
LIBS	Laser Induced Breakdown Spectroscopy
LIDAR	Light Detection and Ranging
LITE	Lasercom Inter-satellite Transmission Experiment
LLCD	Lunar Laser Communication Demonstration
LOS	Line-of-Sight
LPD	Low Probability of Detection
LPE	Low Probability of Exploitation
LPI	Low Probability of Interception
LR-BSDS	Long-Range Biological Stand-off Detection System
LRF	Laser Range-Finders
LRRDPP	Long Range Research & Development Program Plan
LTD	Laser Target Designators
MASINT	Measurement and Signature Iintelligence
MIP	Molecularly Imprinted Polymer
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
MTHEL	Mobile Tactical High Energy Laser
NACL	Navy- ARPA Chemical Laser
NASA	National Aeronautics and Space Administration
Nd:YAG	Neodymium-doped Yttrium Aluminum Garnet
NFIRE	Near-Field Infrared Experiment
NIST	National Institutes of Standards and Technology
NLOS	Non-Line-of-Sight
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
ONR	Office of Navy Research
ORCA	Optical/RF Combined Adjunct
ORCLE	Optical RF Combined Link Experiment
PAT	Pointing, Acquisition and Tracking
QKD	Quantum Key Distribution
QSS	Quantum Science Satellite
QUESS	Quantum Experiments at Space Scale
RAMD	Rockets, Artillery, Mortars and Drones
RDTE	Research, Development, Test and Evaluation
RELI	Robust Electric Laser Initiative
SAR	Synthetic Aperture Radar
SBIRS	Space Based Infrared Sensor
SDI	Strategic Defense Initiative
SERS	Surface-Enhanced Raman Scattering

SFTS	Space Flight Test System
SWaP	Size, Weight, and Power
TALC	Tactical Airborne Laser Communications
TALON	Tactical Line-of-Sight Optical Network
TERS	Tip Enhanced Raman Spectroscopy
THEL	Tactical High Energy Laser
THOR	Terahertz Optical Reach Back
Ti:S	Titanium Sapphire
TOGS	Transportable Optical Ground Station
TRITON	Tactical Relay Information Network
TSAT	Transformational Satellite Communication System
UAV	Unmanned Aerial Vehicles
UV	Ultra-Violet
VCSELs	Vertical-Cavity Surface-Emitting Lasers
WDM	Wavelength Division Multiplexed

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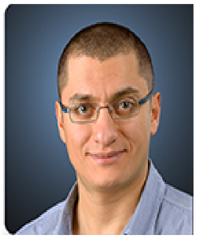

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