DIRECTED ENERGY WEAPONS – COMPONENT OF DISRUPTIVE EMERGING TECHNOLOGY WITH IMPLICATIONS ON STRATEGIC STABILITY –

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Directed energy weapons represent an emerging, disruptive, credible, relevant technology with the potential for use in all military action domains and with the role of influencing the power balance globally.

Given that the nature of the threats has changed in the current security environment, the great powers need a more strategic approach to capitalize on future technologies, including directed energy weapons, in a successful manner. Against the background of escalating tensions in many regions of the globe, emerging technologies are an essential lever for both defence and deterrence. In relation to conventional kinetic weapons, directed energy weapons have some advantages – precision, reduced costs, calibrated effects, possibility to be employed to neutralize vital targets for adversaries without causing collateral damages –, but also some disadvantages: decreasing the force and effect of the radius/beam, relatively range short, impossibility of being employed against the targets located behind some obstacles, low progress in adapting to the needs of the armed forces services and fielding in weapon systems.

Electromagnetic radiation is critical for communications, command and control, navigation, targets acquisition, information collection, surveillance, reconnaissance, missile guidance, early warning, and neutralization of targets, aspects that have propelled the development of capabilities, including directed energy weapons directed, to counteract efficient use of electromagnetic spectrum or to neutralize some targets.

Keywords: directed energy weapons; high energy lasers; high-power microwave weapons; electromagnetic spectrum; drones;

INTRODUCTION

The shifting of world order and the largest technological competition of the last era are in progress. It is increasingly difficult for a superpower to maintain technological supremacy considering the ascension and progress of China but also the technological evolutions of the other great powers. Russia and China, along with their allies, make visible efforts to reorganize the world order and promote their global economic and political interests – actions that threaten the USA status as a global leader (Booz, 2024, pp. 1-10).

Several *emerging technologies* are mentioned in the documents on US national security and the studies on the balance of power and deterrence at the global level. They could have a disruptive impact on the two fields in the coming years as well as significant implications for the arms race, the military concepts of operations, and the future of the war. These technologies include: *artificial intelligence, lethal autonomous weapons systems, hypersonic weapons, directed energy weapons, biotechnology, and quantum technology.*

Directed energy weapons (DEW) are defined as those weapons that employ concentrated electromagnetic energy, to prevent normal functioning, cause physical damage, disable, destroy the equipment, technique, and armament as well as to neutralize the enemy personnel. The *reduced costs* for shots and the *almost unlimited ability to execute fire* transform them into efficient and effective assets, in relation to the conventional ones, to defend against volleys of missiles, and large and dense air group unmanned vehicles.

Theoretically – due to reaction speed – the directed energy weapons could represent a viable option for missiles interception in the boost phase, but experts are not convinced of the feasibility and implementation of this solution. DEW could be employed to temporarily disable or damage the satellites and sensors, an action that could affect intelligence collection operations, military communications as well as the positioning, navigation, and synchronization systems utilized to determine targets. *High-powered microwave weapons (HPMW)*, as part of DEW, *represent non-kinetic means for neutralizing communication and electronic systems, as well as improvised explosive devices.* Also, the possibility of using them for crowd control has been explored (Sayler, Jan. 2024, pp. 1-3, O'Rourke, 2023, pp. 1-20, Sayler, Feb. 2024, pp. 1-3).

We are in a period of an increased competition for superpower status that has as consequence an increasingly challenged security environment, with wars in Europe and the Middle East as well as confrontations in the South and East China Seas. The USA assesses China as the main threat to its national security, closely followed by Russia. Lately, both have supported a large program of investment in science and military technology. China, in order to counteract the US Joint All-Domain Command and Control initiative/JADC2, develops a new military project known as *Multi-Domain Precision Warfare* to modernize its every domain-specific force, from the cyber to the space. Both fundamental operational concepts are based on the interconnection of command and control, communications, computers, intelligence, surveillance, and reconnaissance to quickly coordinate the fire power and exploit the weaknesses of the opponent. The analysts in the defence area claim that DEW will play a key role in what is known as *stratified defence,* having the technology or countermeasures to neutralize multiple threats in complex situations. The implementation of DEW is affected by their technological complexity but also by certain materials, such as germanium and gallium, and the expensive precision components (Demarest, 2024, pp. 1-5).

DEW include *high energy lasers* (HEL), *high-power microwave weapons* (HPMW), and *particle beam weapons* (Sayler, Feb. 2024, pp. 1-3). DEW are part of a set of advanced capabilities and domains that are essential for *deterrence* and *maintaining the competitive advantage* by the great powers. This article analyses some of the consequences of introducing these weapons in equipping the armed forces for global stability (Townshend, 2019, pp. 2-15; Department of Defense, 2022, pp. 1-22).

Emerging technologies are effective for deterrence when potential opponents are provided with sufficient data on a particular system of weapons, to consider it certain, and authentic, and simultaneously, they create uncertainty about the potential of their capabilities (Townshend, 2019, pp. 2-15). The Ukraine conflict has also highlighted a change in the strategy of the great powers generated by the employment in all domains of a broad spectrum of weapon systems and platforms, from conventional to capabilities based on emerging technologies, political and informational war, cultural tools, and sophisticated forms of exercising of power. *The power projection based on the association/combination of the new emerging technologies with the latest hybrid warfare techniques and ambiguous challenges and thresholds determine a new dimension of deterrence*. Adapting to these new realities by adopting effective and firm approaches to this type of deterrence

could be a way of response (Ib.). A new generation of weapons – many based on so-called emerging technology – will enable the forces deployed in the theatre of military actions to discover and strike the targets, timely, precisely, and quickly in all domains of waging battle actions.

The great powers allocate considerable funds to developing DEW – critical and emerging defence technologies – to employ them to overcome the threats presented by drones and rockets but also for use as space-based capabilities. Among the potential applications can be mentioned *HEL* and *HPM, short-range air defence systems (SHORAD) to neutralize unmanned aerial systems (UAS)*, as well as *rockets, artillery, and mortars (RAM)* (Demarest, 2023, pp. 1-12). *NATO has accelerated the transformation and adaptation process to meet current and future threats and maintain technological advantage, including experimentation and more rapid fielding of emerging technologies*. (North Atlantic Council, 2024, pp. 1-6).

The *laser* uses the directed energy to neutralize a target. It is not achieved by heating and melting, there is no reciprocal action of waves, but only a large amount of energy. A beam or energy beam is focused to blind, cut, or cause damage by heating a target. The HPMWs use the electromagnetic spectrum in the air, and space to cancel/stop the ability to operate properly of any system that uses voltage and current. They emit waves of energy that overload or *"fry"* electronic components. Each type of directed energy weapons has *strengths* and *weaknesses*. For a laser to be effective, its system must be able to detect a threat and track it. Even if they are powerful and practical, and the system has relatively small dimensions, the estimated distance at which the current systems operate is approximate 7 kilometres (Demarest, ib.). Moreover, weather conditions and duration of action can still affect their effectiveness. While HPMWs can have a practically instant effect on electronic components, their effectiveness is reduced at greater distances. While HELs can drill different materials, certain atmospheric conditions, including fog or wind, can affect or change the target's result. Given that everything is automated, the platform is dependent on the production, continuity and amount of electricity that supplies it. The armed forces make efforts to materialize the directed energy systems in offensive and defensive capabilities.

In the defence community, it is generally recognized that there is a great gap between the *technology's development, fielding and its acquisition*. Regarding the directed energy weapons – too important technology to be ignored, according to experts – there is a pressure and emergency for acceleration, generated by the Ukraine war, for the necessity to complete the development and implementation process (Ib.). Due to the explosive development of modern technology and accelerated proliferation of armaments, there is a real concern among scientists regarding the effects of science and technology on mankind, positive and negative, potential and real, and especially regarding the role of science and scientists in the balanced evolution of implementation of their results in the military field. As the conflicts in Ukraine and the Middle East continue, the great powers act to make the armed forces suitable for the new reality of warfare and streamline the modernization strategies to cope with the challenges of conducting fighting actions in different domains (Demarest, 2024, pp. 1-5).

Global stability, as a rule, is affected when a great power has military capabilities and the other great powers still do not have the necessary capabilities to counteract them, or a great power can obtain an obvious advantage by triggering a war. If we consider the USA, China, and Russia, the global system will be unstable when, by a first strike, one of these great powers has the capacity to eliminate the entire response capacity of the other. In this situation, none of the parties would have any reason not to initiate the first nuclear strike, but at the same time, each party knows that any total war will produce massive damage, no matter what triggered the first strike, so the situation is relatively stable. The paradoxical consequences of developing weapons that use emerging technology is that the destructive effects on personnel and equipment or the danger of triggering a war are, apparently, reduced, but, in reality, mankind is moving to a volatile and hazardous world (Gertler, 1987, pp. 1-2, 5-15).

DEWs have the potential to change the way of conducting military actions and the nature of warfare, which will have consequences for the national security of the great powers. These implications, among others, refer to: *decreasing the duration from the sensor to the shooter, engaging more targets before the adversary can take action, as they can be used as a sensor and as a weapon; DEW contribute to achieving air supremacy by neutralizing enemy air defence; DEW rapidly locates and attacks the surface-to-air mobile systems*. HPMWs represent antiradiation attack capabilities, deny anti-detection actions, and measures of enemy air defence systems, and attack them by turning off their systems; they can be employed in effects-based precision operations by counteracting the most problematic asymmetric strategies utilized by the enemy: the use of civilians as shields, without hurting civilians in the area; DEW can contribute to limited space control. For defensive purposes, it ensures the security of their own space-based assets, for offensive purposes, it may temporarily deny the employment of the enemy space-based capabilities

and the damage or destruction of enemy satellites (Feickert, 2018, pp. 1-29). DEWs represent an operational advantage source for the owner state of such weapons and then these emerging technologies, once fielded, have the potential to influence the balance of global power. Concerning other capabilities, DEWs have a unique essential characteristic that provokes precise and calibrated effects against multiple targets almost instantaneously at a very low cost with high operational efficiency (Gunzinger, 2012, pp. pp. xiii, 1, 20-28).

Directed energy battle actions are *military actions that entail the use of weapons, devices, and countermeasures with directed energy to incapacitate, provoke direct damage, or the destruction of enemy equipment, technique, and armament as well as the neutralization of the personnel or to interrupt, exploit, decrease or prevent hostile employment of electromagnetic spectrum (EMS) through damage, destruction, and disruption*. They also include actions undertaken to protect friendly equipment, facilities and personnel, and to maintain the employment of their own EMS. These are part of the electronic warfare missions and encompass active technology denial, lasers, radio frequency weapons, directed energy anti-satellite systems, and HPMW systems. (Defense Intelligence Agency, 2022, pp. 41-48, Gunzinger, ib.).

Directed energy (DE) is an expression used to ***depict an extensive range of non-kinetic capabilities that produce a beam of concentrated electromagnetic energy or atomic or subatomic particles capable of damaging or destroying enemy equipment, facilities, and personnel in all battle action domains***. ***Directed energy battle actions*** comprise actions taken to ***protect the own forces' equipment, facilities and personnel, and to secure the employment of the electromagnetic spectrum by friendly forces*** *(*Gunzinger, ib.). The armed forces that develop and field battlefield lasers and HPMW will possess a noticeable military benefit. DEW will complement kinetic weapons and combat emerging threats like drones, fast attack boats, and cruise missiles. Details are provided in *figure 1, 2* and *3*. In *figure 1* incoming drones and missiles are depicted (Demarest, 2023, p. 4).

Some analysts claim that the potential of DEW could change the very nature of war or could ensure states that own such weapons an undeniable advantage, while others emphasize that laser-based projects have not developed at the forecast pace (Feickert, 2018, p. 5).

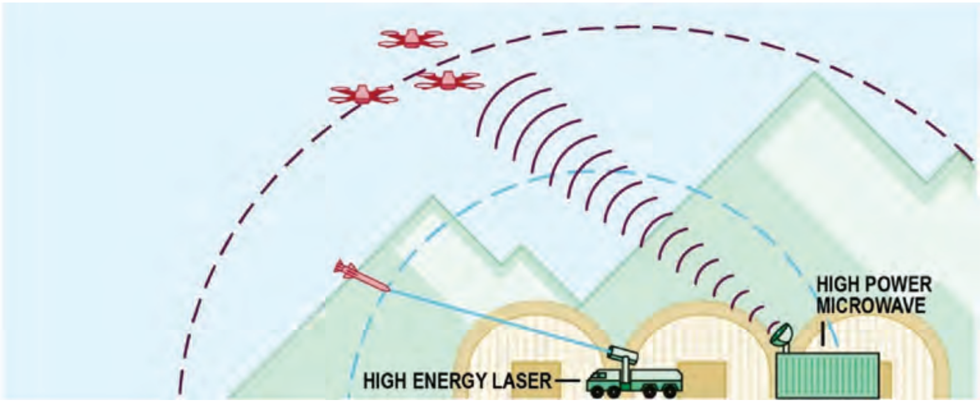

Figure 1: The way in which directed energy weapons can be used in combat (Demarest, 2023, p. 4)

THE LASER – FEATURES, EMPLOYMENT IN BATTLE ACTIONS

HELs use concentrated light to inflict physical damage on a target. By fielding viable weapon systems, DEW has a potential significance in tackling current and emerging threats to neutralize missiles, artillery and mortars, in eliminating certain threats to air defence against short-range assets, and in obtaining success in fighting actions in all domains (O'Rourke, 2023, pp. 1-20). Airborne HELs can potentially transform the nature of the battle in all domains. Aircraft or platforms equipped with HEL can be used for striking ballistic missiles, surface-to-air missiles, unmanned combat air vehicles, surface craft and other air platforms as well as space-based systems and can be successfully employed in carrying out precise strikes on particularly enemy targets extremely defended and also for surface-ships self-defence or ground forces equipment (O'Rourke, 2024, pp. 1-20)

Electromagnetic spectrum. *The electromagnetic spectrum (EMS)* is *the range of wavelengths or frequencies of electromagnetic radiation. It includes radio waves, microwaves, visible light, X-rays, and gamma rays*. As the wavelength of the electromagnetic radiation shortens, the waves have a higher frequency – how quickly electromagnetic waves follow each other – and therefore more energy *(figure 2)*. These waves are called *electromagnetic waves* because they have both electric and magnetic properties. Such waves vary in frequency, wavelength, and energy. Scientists classify electromagnetic waves by their wavelength or frequency. Waves with shorter wavelengths (e.g., gamma rays) have higher frequencies and higher energy; waves with longer wavelengths (e.g., radio waves) have lower frequencies and lower energy (Hoehn, 2022, pp. 1-3). In the military field, most of the communication equipment is based on radio waves and microwaves,

and infrared and ultraviolet spectrums are used for laser technologies and intelligence collection. Infrared and ultraviolet lasers have a greater bandwidth than radio frequencies and allow the dissemination of large volumes (for example, video) for long distances due to signal power. In the military field, lasers can be used as offensive means, to temporarily blind the satellites' sensors, destroy drones, and for other purposes (Sayler, 2021, pp. 1-21).

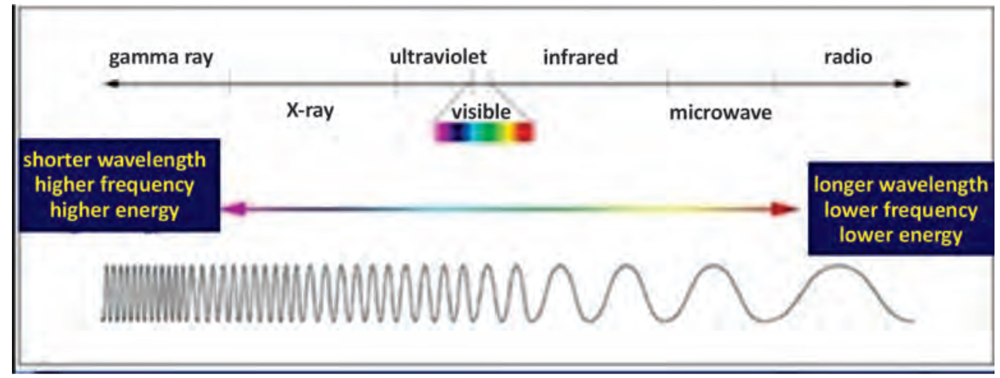

Figure 2: The electromagnetic spectrum (Hoehn, p. 1).

Current military applications of the spectrum. Almost all modern weapon systems, such as those used by aircraft, satellites, terrestrial battle equipment, ships, and radio stations, depend on the spectrum to operate. EMS is also used for: ***Communications*** – data transmission almost instantly between the elements of the elements of the battle array, by using the terrestrial radio stations and the communication satellites; ***Situational awareness*** – the use of radio waves, microwaves and infrared radiation to develop a picture of the battle space, by determining the location of the own forces and the enemy ones. The most common situational awareness applications: passive radar (LIDAR – ***light detection and ranging***), detection and collection of spectrum emissions (SIGINT), infrared sensors; ***electronic warfare*** – the use of EMS to gain and maintain its operational control; ***spectrum operations*** – command and control (C2), signature management (manipulate the spectrum to reduce the electromagnetic signature, and identify and neutralize forces) and navigation warfare (deliberate offensive and defensive actions for efficient use of positioning, navigation and timely use of information simultaneously with denying these actions for the adversary by coordinated employing of space-based, cyberspace and electronic warfare capabilities), command and control and especially for ***Emerging Military Applications***

of the Spectrum (fifth generation – 5G – of communications, use and Applications of Artificial Intelligence, DE technologies-laser communications, DEW, Counter-UAV) (Sayler, 2021, pp. 4-19). *Electronic warfare*, defined as *military activities that use electromagnetic energy to control the electromagnetic spectrum ("the spectrum") and attack an enemy* (Hoehn, 2022, pp. 1-3). Some programs aim to make lasers to solve the capabilities gap to address asymmetrical threats – unmanned aircraft (UAV), small boats, and information, surveillance, and reconnaissance sensors.

The laser *uses electricity to generate photons or light particles*. The photons pass through an amplification medium – an amalgam of substances – that rapidly develop many photons, all having the same characteristics as the initial photon. This fact determines the coherence feature of laser beams – to finally focus on a narrow beam (Boyd, 2024, pp. 1-3). The high-energy laser systems – used in the military field – are based on solid-state lasers that use special crystals to convert the input electrical energy into photons. The main feature of high-power solid-state lasers is that the photons are generated in the infrared segment of the electromagnetic spectrum and, consequently, cannot be seen by the human eye (Gunzinger, pp. 20-28).

HEL Weapons, Potential Advantages and Limitations

The ***main advantages*** are represented by: *the low cost per shot*; *a huge number of shots*; and *the rapid target engagement time*, the light from a laser beam can almost instantly strike a target, causing the target damage in seconds, after which it can immediately engage another target; *the capacity to counteract the guided missiles*, by tracking and maintaining the beam on the missiles*; the precision target engagement*, the laser spotlight emitted can have a several- centimetre diameter and damage only what strikes without collateral damage and calibrated responses, can achieve other effects than the destruction of targets, namely the targets' detection and monitoring or causing non-lethal effects such as the reversible blockage of the electro-optical sensors.

The ***potential limitations*** of the lasers refer to*: the line of sight*, the laser light moves through the atmosphere on a straight trajectory, thus limiting their range. Only the targets located up to the horizon line or those that are not protected by certain shelters will be employed; *atmospheric absorption, dispersion, and turbulence*, the substances in the atmosphere can affect the laser's quality, efficacy, and range. Absorption increases proportionally, in general, with target distance. Rain or fog can prevent the normal functioning of the lasers; *thermal blooming*.

A laser system that engages the same target for a longer period can heat the air through which it passes, this phenomenon alters the quality of the laser beam and reduces the effect on the target; *saturation attacks.* A laser can engage a single target simultaneously, it requires a few seconds to be turned off and redirected to the next target. This determines the maximum limit of targets that can be engaged in a period; *hardened targets and countermeasures*. Lasers with smaller beam powers measured in kilowatts may have a lower efficacy against shielded targets, from ablative material or extremely reflective or rapidly rotating as well as targets using masking measures; *risk of collateral damage to aircraft, satellites, and human eyesight*. The laser radius with ascending orientation, which does not strike the target, continues its movement, with the risk of hitting aircraft, radars, sensors, or satellites and provoking unwanted collateral damage. Light issued by lasers on certain frequencies can cause permanent damage to human eyesight, including blinding. (O'Rourke, 2024, pp. 3-27; 2023, pp. 1-20). The effects of weapons with HEL compared to those with HPM are presented in *figure 3*.

Numerous ***military applications*** use HELs. Among them can be listed: lasers in the infrared and ultraviolet ends of the spectrum to dazzle satellite sensors and destroy drones; the use of emerging communications technologies of lasers – transmitting light, instead of radio waves, between antennas; the use of lasers to disable intelligence collection sensors, destroy small UAS and satellite communications; precision-guided munitions use laser guidance to improve a weapon's accuracy to less than 3 meters (Lucas*,* 2022, p. 1); the development, procurement, and fielding/deployment of high-energy laser weapon systems to counter, destroy UAS – low, slow, small – usually called drones; in covert and clandestine operations for identifying personnel at distances of around 200 meters (Sayler, 2023, p. 1); there is no consensus on the level of precise power that would be needed to neutralize various target sets, certain documents claim that: lasers of around 100 kW (Sayler, 2024, pp. 1-3) could engage unmanned aircraft systems, small boats, rockets, artillery, and mortars, whereas lasers of around 300 kW (Ib.) could additionally engage cruise missiles flying in certain profiles (i.e., flying across – rather than at – the laser), to defend fixed or semi-fixed critical assets against cruise missiles, unmanned aircraft, missiles, artillery, and mortars. Lasers of 1 MW could potentially neutralize ballistic missiles and hypersonic weapons – at a range of up to 20 km; weapons to disrupt, degrade, or damage space-based satellites and their sensors on a low orbit including non-optical satellites; ground-based laser weapons that can damage space-based sensors on a low orbit; higher power laser systems that can degrade non-optical satellites; destructive capabilities that use the laser to disrupt space-based weapons; laser-guided rocket systems; 50-kw laser weapons to defend against air and artillery threats; indirect fire protection capabilities; light detection and ranging – LIDAR is a remote sensing method that uses pulsed laser light to measure the distance, speed, and/or altitude of physical objects to map the surrounding environment. LIDAR allows for precise, accurate, and rapid three-dimensional measurements of natural and artificial environments, with high resolution and long-range detection; LIDAR can also be used to identify and determine the depth of the coast mine fields and for atmospheric monitoring; more powerful laser on the surface shipboard of the navy to counteract a wide range of surface and air targets at ranges up to about 20 km. (Hoehn, pp. 1-3, Sayler, 2024, pp. 1-3, O'Rourke, 2024, pp. 18-21).

Lasers ***are classified*** by the *gain medium* used for light amplification: *with gas-neon helium* for metrology applications, carbon dioxide for material processing; *a semiconductor (diode)* – that contains a semiconductor positive- negative junction. They are the most effective regarding the power-to-cost ratio, high power conversion efficiency, high quantum efficiency, and a wide range of available wavelengths. They are used in telecommunications, materials processing, bar code scanning, medical lasers and LIDAR systems; and, *solid-state lasers* – which use crystals or glass materials doped with transition metal or rare earth ions. They can reach the highest powers from all available lasers and are used for material processing, medical, and military fields (Edmund Optics, 2023, pp. 1-3). *Solid-state lasers* developed for potential use in different environments: *fibre solid- state lasers* fuelled by electrical power, *slab lasers*, and *free electron lasers*. All three types are electrically or chemically powered. At the navy, the existing electricity system on the ship is used (O'Rourke, 2023, pp. 9-14). The increasing use of laser capabilities within the integrated anti-aircraft and missile defence systems is obvious, most likely in the lower level as an altitude of target employment.

For now, DEWs are best suited to fight UAV. The use of laser weapons could be an alternative, less expensive, to rockets-based defence, which can be overwhelmed by multiple targets, against scenarios with small and cheap drones that fly in swarms at low altitudes.

HIGH-POWERED MICROWAVE WEAPONS – FEATURES, EMPLOYMENT IN BATTLE ACTIONS

High-powered microwave weapons, which are part of directed energy weapons, can be used as a non-kinetic means of disabling electronics, communications systems, and improvised explosive devices or as non-lethal *"heat rays"* for crowd control (Sayler, 2021, pp. 1-21). Details are found in *figure 1, 2* and *3*. Conflicts in Ukraine and Israel provide sufficient evidence of the opportunity to neutralize the autonomous drone swarms – asymmetric capability – with low costs, employing non-kinetic weapons, namely HPM.

There are programs for the development of ***two types*** of weapons using HPMs: HPMWs with ***continuous and pulsed waves***. *Continuous wave* HPMWs emit a constant flow of microwave energy in a wide area and can be used in area denial operations against personnel or small electronic devices, such as UAS. *Pulsed wave* HPMWs emit high-power, short-duration pulses of microwave energy, within a wide range of frequencies, from 1 megahertz to 100 gigahertz, and can ensure precise targeting. The weapons that use HPM with a pulsed wave employ a set of specific targets to destroy or degrade their electrical components. ***Knowing the frequency of the target is mandatory*** to determine the energy needed to penetrate the electronic components and obtain the desired effect. The transfer of energy to the receiver/target is determined by the overlap of frequencies, that is, if they are in-band or out-of-band. The amount of energy getting to the target is affected by the way the energy propagates through the atmosphere. The transfer using a narrow band provides a higher amount of microwave energy to the target, but the coupling is harder. In the past twenty years, the HPMW energy sources have evolved, the weight has been reduced and the power of microwaves has increased. In 2003, a 400-kg device produced 20 gigawatts of power and now could produce terawatts of energy making it possible to install these systems on smaller platforms. It has also evolved the distance from which HPMWs can successfully engage a target, from several hundred meters in 2002 to a few kilometres now (McGonegal, 2020, pp. 3-15). Significant progress has been made, particularly by the United States of America, Russia and, China in the development of these weapons. HPMW, due to the high microwave power to be transmitted, are not sufficiently effective at ranges much greater than a few kilometres.

The HPM devices, according to the size of the band they emit, can be classified into two types: ***ultra-wideband*** (UWB), which operate high voltage spikes in impulse-configurated, linked or connected with an antenna to radiate on the range of preferred output frequency; and with ***narrow band***, which operate an electron beam to emit high power radio frequency signals at a particular band frequency. Because the energy is distributed throughout the entire bandwidth, there is a reduced probability that the ***UWB*** sources have the power to damage a device. In a narrow band device due to the ***narrow bandwidth***, there is a risk that the target frequencies do not overlap with the device bandwidth or the target has a strong shielding for the frequency band used by the device, and ultimately the target is not neutralized. Given the complexity of the target shielding, the HPM devices represent effective assets for neutralizing electronic devices (Green, 2022, pp. 71-73).

Among the goals of ***military applications*** using HPMW can be listed: to defend aircraft against surface-to-air missiles; relevant enhancement of the antiradiation attack capabilities and counteracting the enemy air defence systems actions to avoid detection and attack by turning off their systems; neutralization of WMD facilities that are sheltered, fortified or placed near areas with population or civil infrastructure; engagement in conducting precise effects-based operations; they can practically attack any electronic system without doing direct harm to civilians near the targets; disruption of the electricity production and distribution in the short term or the destruction of subsystems; the conduct of strategic strikes against industrial systems and military infrastructure, dependent on electricity and electronic systems; for offensive purposes, they can temporarily deny the employment of space-based assets by opponents and cause the destruction of enemy satellites (Feickert, 2018, pp. 1-29; Walling, 2020, pp. 11-17).

Some studies contend that HPMW can damage computer networks, neutralize drones, swarms of drones, and missiles. At the same time, they can be used effectively against mines and minefields, especially intelligent mines. Analysing microwave sources with different output spectra has showed that narrowband sources are more effective, but broadband sources are preferred to excite resonances in electronic packages. All types of HPM devices use a source of pulsed power, on which the effectiveness in battle depends. The delivery of HPM to the target can be done using fixed assets, which do not involve complex technologies or miniaturization of critical components (antenna and the source) so that it can be transported to the target with the help of a missile (Green, pp. v- vi).

The power source of HPMW can be placed on cruise missiles, but also on the aircraft, to transport and launch them. The missile trajectory and target list are scheduled before taking off the aircraft that is launching these missiles. Once launched from the aircraft, the missile will fly the payload – HPM – on its pre-programmed trajectory, enabling it to strike the planned target. Each weapon that employs HPM realizes effects on the target, but the way and the means with which HPM will be

transported to the target are diversified, including autonomous systems. The HPM technology will evolve by creating several options to mount this technology on different, new, or old platforms to become a feasible technology. The effectiveness of HPMW depends on the significant support of intelligence for effectively tracking targets and identification of the radar frequencies and target systems of the enemy. Knowing detailed information about the target allows the employment of a narrow band that ensures the maximum energy delivery to the target to degrade the electrical components (McGonegal, 2020, pp. 3-15). Microwave weapon systems differ from those specific to electronic warfare – limited to jamming – even if both use frequency spectrum against enemy electronics. Microwave weapons – having lasting effects, enemy electronic systems do not have to be in operation, and protection against them involving actions at the system level as a whole – are used to penetrate electronic systems and overwhelm the ability of a target to reject, disperse, or withstand to the energy received (Walling, 2000, p. 2).

HPMS can disable or destroy the electronic equipment used by the adversary. A swarm of drones can be neutralized – degrading the electronic circuitry in drones due to excessive thermal heating, destroying semiconductor junctions or changing memory states in firmware and generating processing errors – by emitting a single short high-power pulse in the gigahertz frequency range. The effectiveness is higher when the pulse's centre frequency coincides with the circuits' resonances. The efficacy is determined by the synchronization of the waveform through which the necessary power for the complete neutralization of each drone in the group is transmitted, at an adequate distance that makes the enemy's operation not have the desired effect (Green, 2022, pp. 1-10). HPMWs, due to the wider effect area, become ideal assets for destroying missions of large drone swarms.

HPM pulses' effects on an electronic device are conditioned by several factors, and can cause ***damage*** or ***upset***. If the electric field magnitude generated by the HPMW pulse has considerable or relatively large dimensions so that it can puncture the oxide layer of semiconductors within the device or causes cascading outcomes on the frequency bands used for data transmission, the result is ***damage***. If the voltages induced in the electronic device are satisfactory or acceptable in quality or quantity to cause a modification of the binary information transmitted or stored in the device or to change the semiconductor switching status within the device, the result is ***upset***. Therefore, according to the physical laws of electromagnetic propagation, the same HPMW pulse could upset electronic devices at a greater range than the distance at which the damage would be caused (Green, pp. 1-10, 71-76).

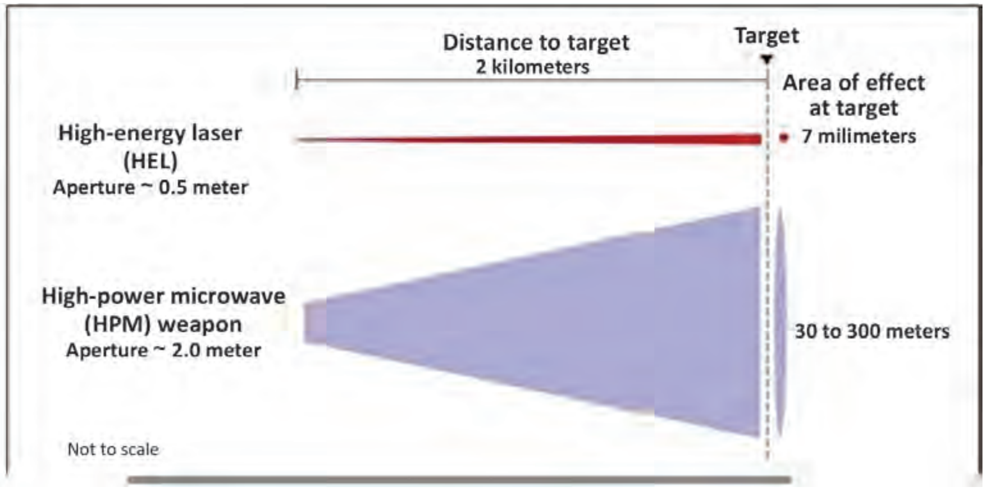

Figure 3: Illustrative effects of HEL weapons compared to HPMW (O'Rourke, 2023, p. 2)

Potential Advantages and Limitations of HPM Weapons

The ***main advantages*** are represented by: *unlimited capacity to execute the fire*; *low cost per shot*; *short time to engage targets* and calibrated responses; *temporary or system-specific effects*. HPM weapons can generate different frequencies and power levels to temporarily or permanently disrupt the electronic systems established as targets without affecting other systems; *extensive effects*. HPM weapons can destroy many unshielded military or commercial electronic systems. Supplementary, they can disable any electronic system located in their electromagnetic cone; *non-lethal applications*. Particular HPM weapons, such as the *"heat rays"*, could represent a non-lethal anti-personal capability in situations in which otherwise the lethal force would have been used; *limited collateral damages*. HPM weapons do not produce collateral damage to physical structures. This feature makes them suitable for actions in urban areas or for punctual situations.

The ***potential limitations*** of the HPM refer to: *constraints about range*. The HPM beams are more diffuse than the lasers and have a lower effect concentration capacity. Therefore, the energy per surface unit decreases in proportion to the distance and the range at which the desired effects can be produced; *fratricide risk*. Because HPM weapons affect all unshielded electronic systems within the range, the own forces systems must be shielded or removed outside the range; and, *the effectiveness of the countermeasures*. The targets shielding favours the absorption of electromagnetic radiation, accordingly, HPM weapons can become ineffective against shielded targets (O'Rourke, 2023, pp. 1-20).

CONCLUSIONS

The conflicts in Ukraine and the Middle East have shown that the threat environment is changing and emerging technologies are increasingly relevant in conflict, modern war, deterrence, and global power balance. The great powers develop programs, in the long and short term, to successfully capitalize on the technologies of the future to identify, research, make prototypes, and subsequently be fielded as operational weapons. Because most joint military actions depend on or are based on the use of electronic devices, the great powers have invested in programs and technologies for the improvement of these assets but also to counteract the operation of these devices.

DEW – unique capabilities – can contribute to coercion by conventional means able to be employed in military operations to change the opponent's behaviour and they can have as target elements that are vital to the enemy state. Due to these possibilities, DEWs represent capable and credible assets that contribute to deterrence and victory in a total war. The DEW – a key element in future wars – can be deployed, by the great powers, in different regions of the globe in situations that are below the threshold of the war, in response to different military actions of some states that represent threats and carry out hostile actions against them. The employment of DEW can lead to communication breakdown in a country by destroying the electrical components, thus limiting the normal working of vital functions in a society and the ability to carry out military actions. DEW can be used for crisis management situations. Currently, many technologies employing directed energy have passed the design-development and manufacturing phase and are in a phase of becoming operational weapons. The procurement of DEWs installed on several different platforms ensures new and innovative ways to neutralize relevant targets and contribute to maintaining the competitive advantage over the adversaries.

DEW represents emergent technology and offers flexibility in making decisions and the possibility of conducting overt or covert actions against adversaries. DEW may represent additional assets to conventional weapons by acting as a viable force multiplier and an option to respond to complex threats. It can be successfully used in disrupting the decision-making centres and communications centres, as well as in disrupting the command-and-control processes. The widespread use of drones in the Ukraine war has led to an equally high demand for anti-drone equipment. DEW is an alternative option, an effective defence asset against armed UAS attacks, widely used in the Russian-Ukrainian war and other regional conflicts. Given that in conflicts drones with low costs and high autonomy are widely employed, the air defence should be adapted and equipped with highly autonomous non-kinetic assets.

Weapons using directed energy are effective and have been implemented in the operational field, with the potential to be diversified in the next years. DEW represents a disruptive emerging technology that is used and developed by great powers to keep competitive advantage.

An important lesson of the latest conflicts is that achieving success in modern war is also conditioned by the rapid and efficient capitalization on emerging technologies in military operations.

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