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Continued Optical Sensor Operations in a Laser Environment

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Continued Optical Sensor Operations in a Laser Environment

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The United States and other nations are developing laser (i.e., "light amplification by stimulated emission of radiation") applications, including high-energy lasers (HEL) and low-energy lasers (LEL). While HELs will likely have military applications in ballistic missile defense (BMD), counter-air, counter-space, and counter-intelligence, surveillance, and reconnaissance (ISR); HEL applications will be slow to proliferate to many potential adversaries due to high cost and technical complexity. However, LELs will be developed as technological byproducts of HELs and commercial applications, and will rapidly proliferate, even to resource-constrained actors, due to low cost and reduced technical complexity.

By 2030 the Air Force will field air and space vehicles which will use focal plane arrays (FPA) as optical sensors. This paper argues that these sensitive FPAs will be vulnerable to LEL attack, which as LELs proliferate, could render the USAF's sensing technologies ineffective. Further, this paper makes the case that the Air Force must continue to investigate the effects of lasers on FPA sensors to better understand how to protect them, and then invest in the technologies to permit continued operation of all FPA sensors in future hostile environments.

To explore this thesis, this paper introduces the basic theory of lasers and focal plane arrays. It then discusses the regimes of future Air Force sensor operations, and analyzes the factors which could facilitate denial of optical sensors using LELs. This paper then looks at the basic methods of sensor protection against laser illumination, and makes recommendations for the Air Force to retain use of optical sensors in a proliferated LEL environment.

Optical Region of the Electromagnetic Spectrum

This research concentrates on effects in the visible and adjacent regions of the electromagnetic (EM) spectrum, as these are where FPAs provide imagery. These regions include the ultraviolet (UV) from 10–400 nanometer (nm); visible, or electro-optical (EO) from 0.4–0.7 micrometer (μm); the near infrared (NWIR) from 0.7–3.0 μm; midwave IR (MWIR) from 3.0–6.0 μm; and the long-wave IR (LWIR) from 6.0–15.0 μm in the EM spectra. The actual usable IR spectrum is discontinuous and less than depicted above, due to various regions of atmospheric absorption (fig 1).[1]

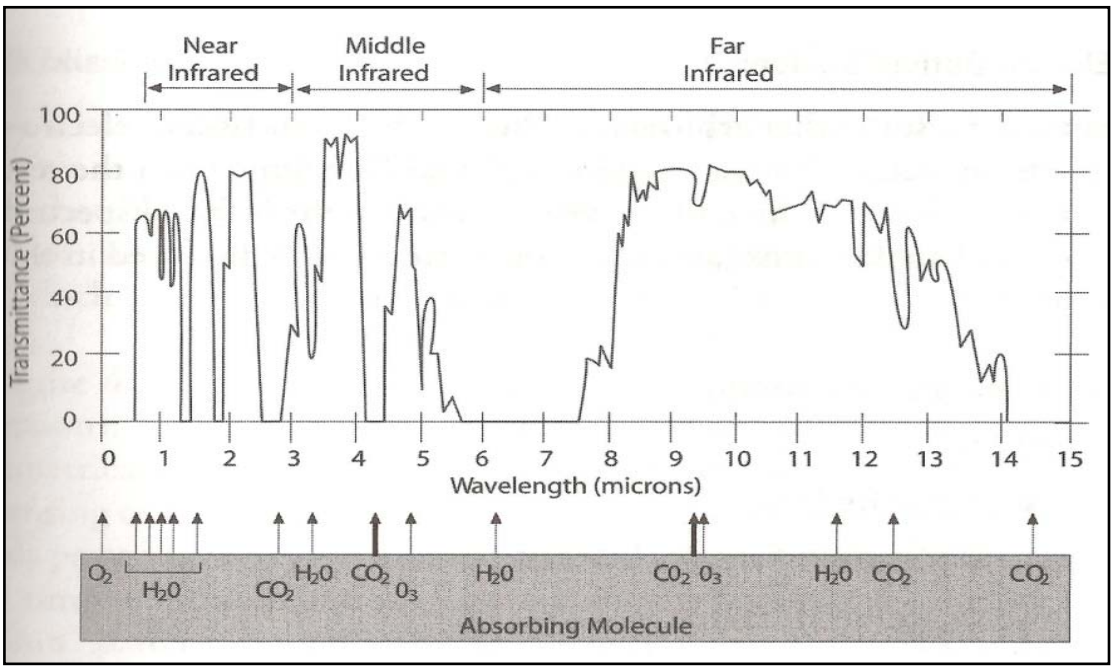

Figure 1. Regions of atmospheric absorption. Percentage of atmospheric transmittance is shown on the vertical axis, while wavelength is shown on the horizontal axis. Note that atmospheric transmittance is high in the 400 nm to 2.5μm region (visible and near IR), 3.0–5.0 μm (middle-IR), and 8.0–14 μm (far-IR) regions [the areas on the chart where the graph is at its highest]. These are the spectral regions in which imaging sensors, including focal plane arrays, are most likely to be effective. (*Reprinted from* David Adamy, *EW 102 A Second Course in Electronic Warfare* [Boston, MA: Artech House, 2004], 81).

Introduction to Lasers

A laser uses an energy source to excite electrons in an active medium to produce a high-energy output of coherent light within a narrow frequency range. Ideal characteristics for lasers are high directionality and low divergence (i.e., narrow beam width), high polarization (i.e., electric and magnetic field vectors on the EM wave front are aligned and synchronous), low diffraction (i.e., very little spreading of the wave front from the laser aperture), efficiency (i.e., high ratio of output power to input power), low jitter (i.e., high reproducibility from

pulse to pulse), and high intensity (i.e., power density on target, in Watts/centimeter [cm]^2).[2] One could also add practical factors such as cost, safety, size, portability, durability, and availability. To date, no one laser design has maximized all of the above factors, which explains the wide variety of lasers in use today and projected for the future. Optimally, one wants to transmit the necessary amount of energy to the target to achieve the desired effect in the desired amount of time.

Lasers are used in a variety of commercial and military applications. Commercial applications include welding, fabrication, biomedical, ophthalmology, dentistry, spectroscopy, environmental mapping, and telecommunications.[3] Several key areas of modern research which are advancing the study of lasers are fiber-optics, free-space laser communications, uranium enrichment, and controlled nuclear fusion.[4] Military applications include distance measurement, defensive countermeasures against EO/IR guided missiles, target illumination, HELs for ballistic missile defense and counter-air. The wide variety and utility of commercial and military lasers indicate that the development of lasers which can threaten our sensors is highly probable.

Focal Plane Arrays

Focal plane arrays are the current and emerging technology for sensing and target detection in the EO, IR, and ultraviolet (UV) spectra. FPAs utilize the photoelectric effect to detect photonic energy. This is important, as virtually every major sensor in our battlespace uses this

phenomenon to let the warfighter "see" what is going on in the battlespace. This is true for sensors in the visual spectrum, as well as the UV and IR spectral areas defined above.[5]

Many FPAs use charge-coupled devices (CCD) which consists of arrays of semiconductor optical receivers designed to detect photonic quanta. Each cell of the array detects a quantum of light energy, and clocks the result to the next cell. The result represents the total original image at the output of the CCD. Figure 2 shows how images are captured on a CCD and then transmitted to a temporary storage area, where subsequent light measurements are integrated in order to detect very minute signals.[6]

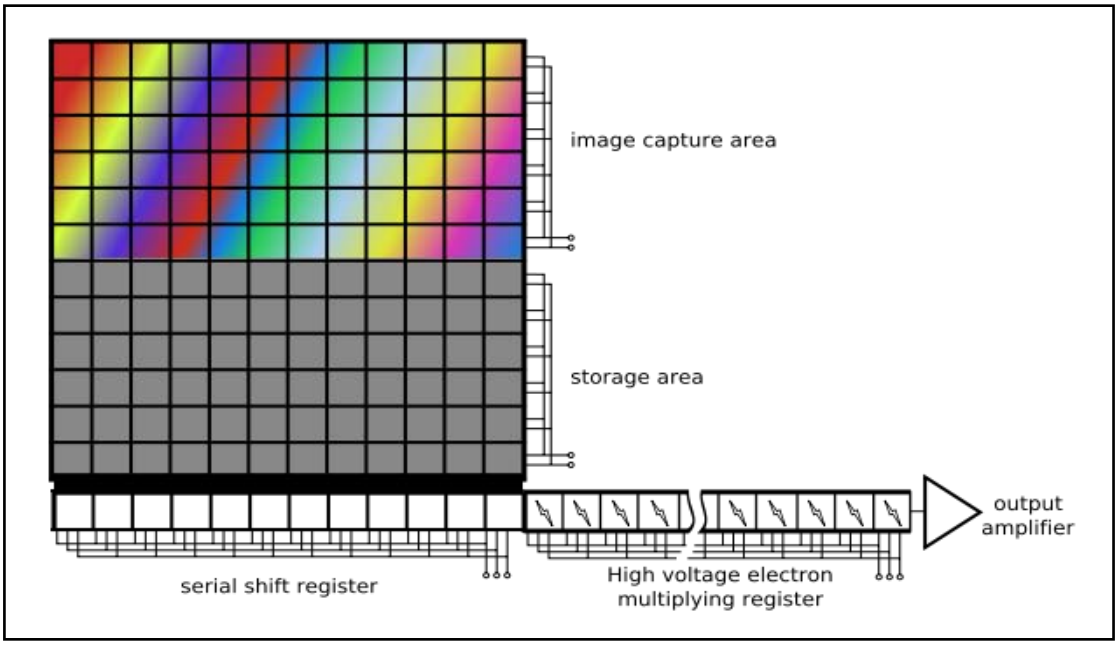

Figure 2. Charge Coupled Device (CCD). (*Reprinted from* Wikipedia, http://en.wikipedia.org/wiki/File:EMCCD2_color_en.svg.

FPAs are fabricated using very-large scale integrated circuit (VLSI) technology. Therefore FPAs, like all VLSI circuits, with time tend to

decrease in size and increase in complexity in accordance with Moore's Law. In current FPAs, the photosensitive detectors are arranged in linear arrays of pixels, where the detector resolution is defined by the spacing between the pixels. Modern CCDs have detector spacing on the order of 5-10 μm, and contain between 5,000 to 10,000 elements per scan line.[7] These basic criteria determine the performance of the imaging sensor. For example, ground resolution is a function of pixel size, focal length, and altitude, and is expressed by

$$Ground\ Resolution\ (m) = \frac{pixel\ size\ (m)}{focal\ length} \times altitude\ (m)$$

The swath of one scan line is a function of the number of pixels and the ground resolution:

$$Swath\ (m) = \#\ of\ pixels\ per\ line \times ground\ resolution\ (m)$$

The photonic energy is a function of frequency and wavelength and is expressed by

$$E = \frac{hc}{\lambda}$$

Where E is the band-gap in electron volts (eV), h is Planck's constant 4.136×10^{-15} eV · s, c is the speed of light 3.0×10^{8} m/s, and λ is the light wavelength in meters. For example, the photonic energy of blue light, which has a wavelength of 435.8 nm, is 2.85 eV.[8]

The choice of material for the semiconductor is determined by the desired receiver wavelength, as the band gap energy of the semiconductor must correspond to the energy of the photon. For

example, the band gap of Silicon is 1.12 eV, which is most efficient at 1.1 μm and which corresponds to the visible and near IR band.[9]

The MWIR and LWIR regions require semiconductors such as indium antimonide (InSb) or mercury cadmium telluride (HgCdTe). As the band gaps in these regions are smaller, thermal distortion becomes significant and can cause interference. Therefore, mid- and long-wave IR receivers typically require cryogenic cooling and are thus more complex, more expensive, and subject to higher failure rates.[10] Figure 3 illustrates some of the substrate combinations matched with light wavelengths and expected sources.

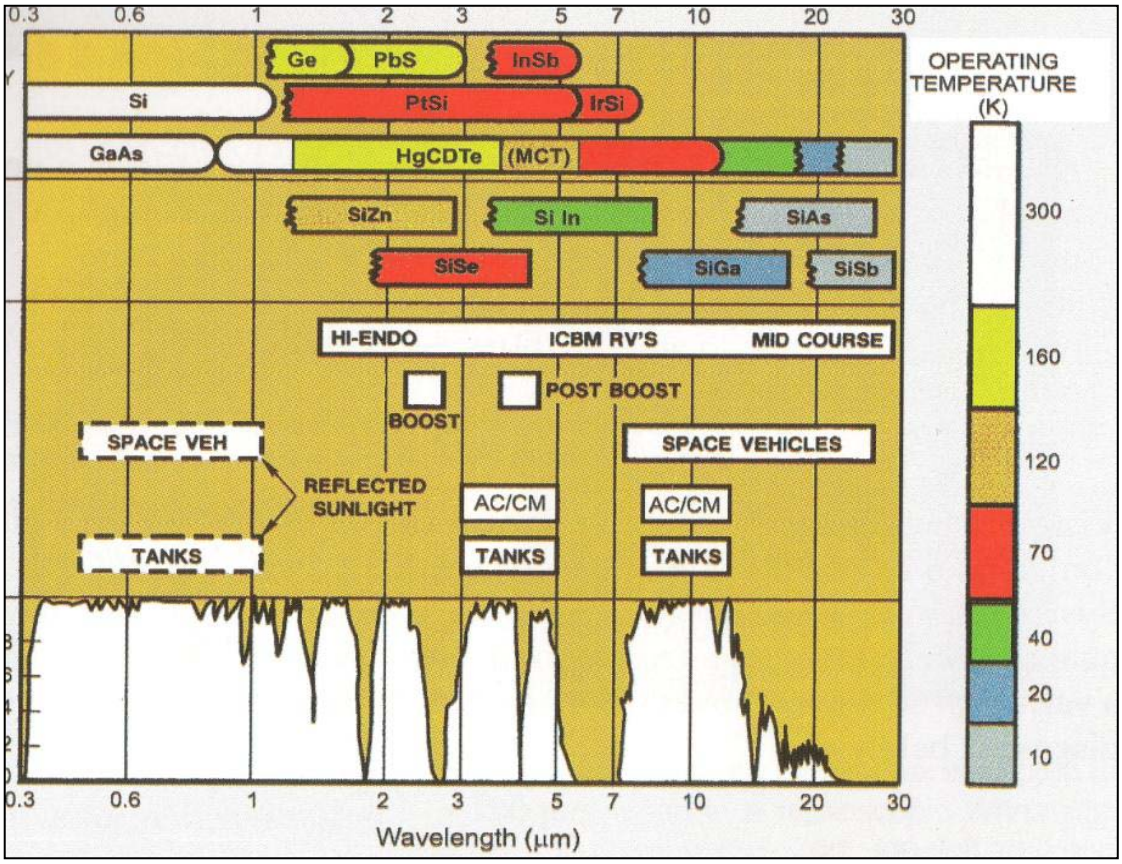

Figure 3. Semiconductors arranged by band gap to cover EO/IR spectrum. Courtesy of Boeing. (*Reprinted from* R. C. Olsen, *Remote Sensing from Air and Space* [Bellingham, WA: SPIE Press, 2007], 77.)

FPAs are usually "multispectral" and consist of semiconducting materials grouped into several bands, each containing thousands of individual detectors. In order to continuously detect light from the EO through LWIR bands, a modern multispectral FPA contains silicon (Si), germanium (Ge), InSb, HgCdTe, and silicon antimonide (SiSb) detectors. A sample FPA from the LANDSAT 7 imagery satellite is depicted in figure 4, and the spectral response of LANDSAT bands is shown in table 1.

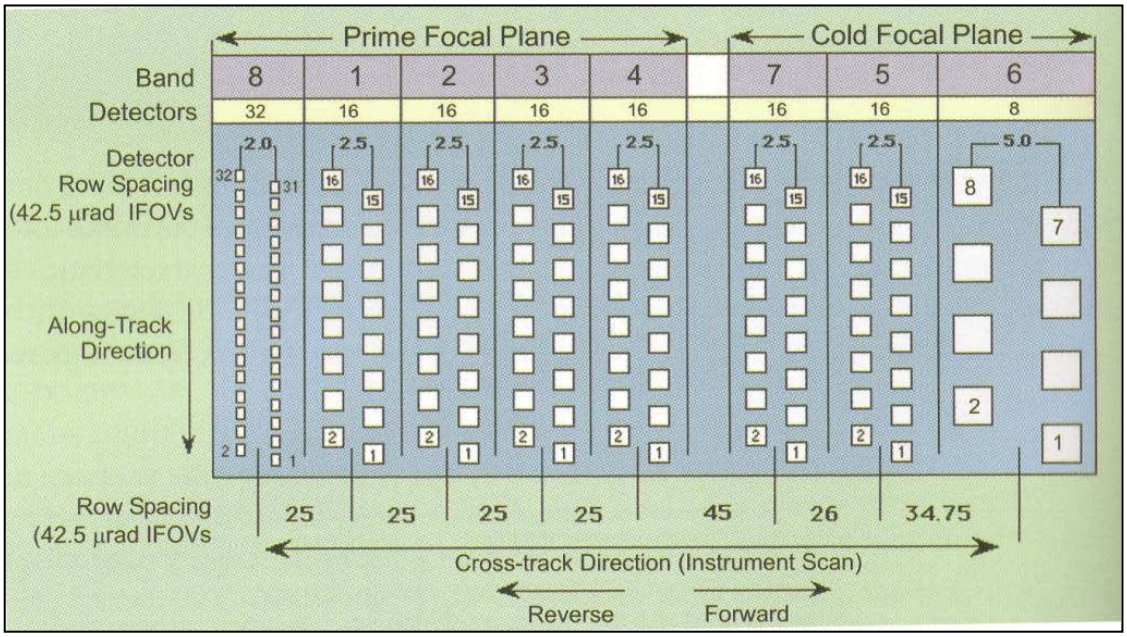

Figure 4. LANDSAT 7 focal plane design. IFOV is "instantaneous field of view," which is a common measure of spatial resolution of a remote imaging system. An IFOV of 42.6 µrad is equal to 2.44X10-3. (*Reprinted from* Olsen, *Remote Sensing from Air and Space*, 124.)

Table 1. LANDSAT 7 focal plane bands and spectral response

Band	Spectrum (μm)	Type	Band	Spectrum (μm)	Type
1	0.45-0.52	EO	5	1.55-1.75	NWIR
2	0.52-0.60	EO	6	10.4-12.5	LWIR (thermal)
3	0.63-0.69	EO	7	2.08-2.35	NWIR
4	0.76-0.90	NWIR	8	0.50-0.90	Panchromatic

Reprinted from Bill Sweetman, ed., *Jane's Space Systems and Industry 2007-2008* (Alexandria, VA: Jane's Information Group, 2007.)

Optical sensors are subject to degradation and destruction from both natural and manmade sources. As the physical dimensions of integrated circuits decrease with improved design, lithography and fabrication technologies, voltage, currents, resistances, and capacitances also decrease, thus increasing device complexity and increasing the impact of outside disturbances on proper operation. It is important to understand some of the ways in which integrated circuits (IC) can fail.

Nondestructive Failure

Some failure mechanisms in ICs cause only temporary degradation. Each FPA component, including detector, amplifier, filter, and converter, has an established dynamic range (i.e., the difference between the smallest and largest signals which can be processed). Photonic energy which is stronger than the maximum detector range will drive a corresponding transistor above the linear (i.e., useful device range) and into saturation (i.e., non-useful device range). If not

attenuated, nonlinear detector outputs would drive downstream components into saturation as well. Properly designed ICs are unlikely to sustain permanent damage if components are capable of attenuation. Additionally, excessive thermal noise margins and spurious "latch-up" caused by transient currents or voltages can require device reset, but do not necessarily cause catastrophic failure of ICs. The effects that cause these failures are also known as "soft" or "reversible."[11]

Destructive failure

The majority of failure mechanisms in ICs are catastrophic (i.e., permanent device failure). These include Fowler-Nordheim Tunneling, drain punch-through, impact ionization (i.e., "hot electron effect"), and thermal runaway. The effects that cause destructive failures are also called "hard" and "nonreversible."[12] Many of the above mechanisms have remedies which are applied at VLSI foundries, such as grounding connections, guard rings and internal short circuit protection—which all increase the size, complexity, and cost of the device. Extensively grounded substrates, in particular, are required for space hardening of ICs against ionizing radiation.[13]

Although understanding the effects radiation on FPAs (particularly spaceborne) has long been a subject of study, research in understanding the effects of intentional laser radiation on FPAs, as well as the protection of FPAs against lasers, is a relatively immature field. Some recent examples of this type of research include examining radiation

effects in indium gallium arsenide (InGaAs) FPAs, radiation hardening for IR-detecting FPAs, extending the frequency response for space-based FPA in the UV and near IR, and using dynamic sunlight filters (DSF) to increase dynamic range in high-light intensity.[14] In one analysis of laser-dazzling effects on IR FPAs, Schleijpen showed how pulsed lasers produce nonlinear degradations in detector response, which are not easily characterized and are difficult to predict.[15] In another analysis, Hueber et al. identified transient and permanent degradations to an InSb FPA detector when irradiated by an in-band semi-conductor laser, and also attempted to qualify the "dazzling efficiency" of a laser on an FPA.

Possible parameters used to qualify dazzling efficiency included the number of saturated pixels, the decrease in signal-to-noise ratio (SNR), the loss of image contrast, and the impact on pattern recognition. The authors concluded that "even though some studies in the open literature show the vulnerability of imaging systems to laser dazzling, the diversity of analysis criteria employed does not allow the results of these studies to be correlated."[16] For example, a continuous wave laser degraded pattern recognition of the target image to a greater degree than an equivalent pulsed laser, and the increase of laser fluence on the detector did not linearly increase the image degradation.[17] The above studies illustrate the point that the effects of intentional laser radiation on FPAs are not well understood.

To summarize the above, modern EO, IR, and UV imaging sensors are FPAs, which consist of complex arrays of thousands of elements of solid-state optical detectors in multiple sensing bands. There are many ways to disrupt these sensitive electronics. Laser irradiance is one way to temporarily deny or permanently damage FPA sensors, and the complete effects of intentional laser irradiation on sensitive sensors are not well understood.

Future Air and Space Vehicle Regimes

While precise remotely piloted aircraft (RPA) roadmaps are constantly in flux due to changing requirements, planning assumptions and budgetary constraints; the Air Force, as well as the other military services and government agencies, will be operating a panoply of remotely piloted and autonomous air and space vehicles during the 2030–2040 timeframe. These vehicles will operate in three basic regimes: near earth, near space, and space. The near earth vehicles will continue to consist of the highly successful RQ-4 "Global Hawk," MQ-1 "Predator," and MQ-9 "Reaper" variants and follow-on series. They will be joined by vertical takeoff air vehicles such as the MQ-8 "Fire Scout," Aurora "Golden Eye," AeroVironment "Sky Tote," and by at least one fully autonomous unmanned combat aerial system (UCAS), such as the Boeing X-45C "Phantom Ray" and/or Northrop Grumman X-47 "Pegasus."[18] The near space regime will be populated by a host of new vehicles as a more economic alternative to space, and will consist of high

altitude long endurance (HALE) RPAs, high altitude airships (HAA, also called "pseudolites"), and tethered aerostats.[19] Although the United States present and future space orders of battle are classified, one can surmise that there will be a host of earth-sensing commercial imagery satellites between 2030–2040, such as the national polar orbiting environmental satellite system, the NASA Lewis and Clark hyperspectral imagery satellites, French SPOT[20] satellites, Israeli earth remote observation satellite, and China–Brazil earth resources satellite.[21]

These remotely piloted and autonomous aerial and space vehicles will perform a wide variety of functions across the spectrum of warfare, including offensive and defensive counter air, targeting, close air support, ISR, and communications. The preponderance of vehicles in all three regimes will be imagery intelligence capable, and will use FPA imaging sensors, such as the L-3 Communications Sonoma MX-12D Skyball II and Sonoma 494 high altitude EO/IR imaging system.[22] Government research and development organizations are also focusing on low size, weight, and power FPAs for micro-RPA applications, including noncooled LWIR sensors.[23]

Analysis of Optical Sensor Vulnerability to Lasers

In the preceding paragraphs, we have shown there are a variety of commercial and military laser applications. We have also seen that the FPA is a complex instrument which is vulnerable to natural and manmade phenomena, and that FPA-based imaging sensors will be

employed on an increasing number of air and space platforms in various regimes with respect to distance from the earth. While there has been extensive research on the use of HELs for target destruction, it remains to be seen whether LELs can be militarized to deny or degrade FPA sensors on air and spacecraft. The following paragraphs will analyze the dangers to optical sensors posed by low-energy lasers.

LEL versus HEL

Much of the discussion is dependent on the definition of LEL versus HEL. There is no absolutely correct delineation—the difference depends on the source, the intended target, and the desired effect. For example, one possible demarcation is "destruction" (HEL) versus "degradation" (LEL). By this definition, industrial lasers (such as carbon dioxide lasers), operating in the 10–20 kilowatt (kW) range, cut through titanium at 3500 millimeter/min.[24] However, this destructive effect takes place at a distance of 10 cm, and is not practical at ranges of tens—hundreds of kilometers (km), due to target tracking, beam divergence, diffraction, and atmospheric effects. In another example, one could state that LEL are those lasers marketed to the public as "recreational" (i.e., "nonprofessional"), which historically were those lasers marketed at ANSI Class 3 and below.[25] However, 1.5 watt (W) lasers are now marketed to the general public as "recreational" and the effects of these lasers are sufficiently threatening to aircraft that the US Congress has debated new regulations and increased legal oversight.[26] An additional delineation

between HELs and LELs is that high powered (i.e., 10–100 megawatts) weapon-class lasers are subject to a nonlinear atmospheric effect called thermal blooming, where atmospheric absorption creates additional refraction. In low-powered lasers, the characteristics of the transmitted radiation have little effect on the atmosphere.[27]

Given the above, the best definition of "low-energy laser," for the purposes of this paper, is a laser which has industrial or scientific uses, is commercially available, has a continuous power output of less than 10 kW, and is not subject to nonlinear atmospheric absorption effects.

Tracking and Targeting

The susceptibility of an FPA sensor to laser countermeasures varies according to the regime in which it is operating. For example, in the near earth regime, the sensor is close to the earth and laser source (less than 60,000 feet), but is maneuvering with nondeterministic motion, often at high accelerations relative to the laser. In the near space regime, the sensor is further from the earth (60,000 to 100,000 feet) but is stationary or quasistationary, with only minute motion relative to the laser. In the space regime (considered to be low Earth orbit [LEO] in this research), the sensor is much further from the earth (600–1000 km) and is moving at a high rate of speed across the sky, up to 18°/second depending on altitude.[28] However, the path of the sensor is determined by orbital mechanics and is highly predictable.

One factor in estimating susceptibility of FPA sensors to lasers is the adversary's ability to track the target. The laser must continuously illuminate the sensor—either for tens of seconds to damage a sensor, or indefinitely, if the desired effect is to deny use of the sensor. For the space regime, all nations with a space-launch capability in the 2030-2040 timeframe should be assumed to have the ability to continuously direct a low-power laser at a LEO satellite. Although one cannot be certain that nonstate actors will have this capability in 2030–2040, commercially-available equipment already allows amateur astronomers to track satellites in LEO.[29] Open-source satellite tracking optics, combined with the evolving field of laser communications, could result in high-precision laser satellite tracking equipment becoming available to the commercial market.

Continuous laser illumination of an FPA on an aircraft in the near earth regime is, and will remain, a challenging technical problem in the 2030–2040 timeframe. NATO allies lead the world in technologies to track highly-maneuvering targets using LEL. Some examples are the AN/AAQ-24 directional infrared countermeasure (DIRCM) and follow-on large aircraft IR countermeasure (LAIRCM), which direct IR lasers at an attacking missile.[30] Russia, France, Germany, Sweden, and Israel also produce a large range of directional laser warning systems, electro-optic fire control devices, and laser rangefinders which could be adapted to continuous laser illumination.[31] Nonstate actors will have difficulty

acquiring this technology in a legitimate venue as there is no commercial market for EO/IR tracking of highly maneuverable targets.

FPA sensors are most susceptible to laser countermeasures in the near space regime. Stationary tethered aerostats, "quasistationary" high altitude airships at 65,000 feet, and pseudolites operating below 90 knots at 70,000 feet will provide lucrative targets for ground-based LEL.[32] Aircraft operating in this regime are not likely to be operated in high-threat airspace, as they are vulnerable to high-altitude surface-to-air missiles and counterair threats. They will likely be operated over lawless and ungoverned areas, where they will provide persistent surveillance against nonstate actors. Their imaging sensors, however, could be susceptible to laser disruption by nonstate actors.

One of the key limitations of achieving high laser intensity (W/cm^2) on a target at long distances (10s–100s of km) is the scintillation effect caused by atmospheric turbulence. The solution to this technical challenge is adaptive optics. Adaptive optics is complex and expensive. They require an auxiliary laser to sample the atmosphere and provide environmental information to a wave front phase computer, which in turn activates tens of thousands of microhydraulic actuators on a deformable mirror, varying the surface from 1–10 μm every millisecond.[33] The potential growth of free-space laser communications, however, could reinvigorate commercial research and development (R&D) in adaptive optics. This could catalyze the proliferation of technology which could

improve the ability of smaller states and nonstate actors to track and engage distant targets with LEL.[34]

Empirical Analysis of the Danger of Sensor Saturation by LEL

The following brief empirical analysis shows the vulnerability of FPAs to LEL saturation effects. Each individual detector cell must be extremely sensitive to detect its target energy at great distances. For example, the formula for radiated power for a blackbody (i.e., naturally radiating) source is

$$R\left(\frac{W}{m^2}\right) = \sigma\epsilon T^4$$

Where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W/m^2·°K^4), ε is emissivity (where an emissivity of 1 signifies a perfect blackbody), and T is the temperature of the source in degrees Kelvin (°K).[35] The source radiations of objects in the visible bands are assumed to perfectly reflect solar radiation, which averages 1367 W/m^2 at the equator.[36] Table 2 shows the source radiation intensities at several wavelengths of interest.

Table 2. Radiation levels of selected sources.

Temperature (°K)	900	500	300	Visible Reflection
λ_{max}	3μ	6μ	10μ	600 nm
Total radiation (W/m^2)	3.7×10^5	3500	500	1400

Free-space propagation losses, which are assumed to be isotropic, are given by the formula

$$L = \left(\frac{4\pi S}{\lambda}\right)^2$$

where s is the distance in meters.[37] A logarithmic method of computing $1/s^2$ propagation losses is as follows:

$$L_s\ (dB) = 32.4 + 20\ \log_{10}\ (km) + 20\ \log_{10}\ (MHz)$$ [38]

Using equations 5 and 6, table 3 shows the corresponding propagation losses in dB and the resultant power levels at the sensor at a given distance from the source. Note that this calculation does not take into account scattering or absorption effects.

Table 3. Power levels at a detector with distance from the source as indicated.

λ	5km (dBW)	5km (W/m^2)	10km (dBW)	10 km (W/m^2)	25 km (dBW)	25 km (W/m^2)	800 km (dBW)	800km (W/m^2)
600 nm	-189	1.3×10^{-19}	-194	4.0×10^{-20}	-217	2.0×10^{-22}	-247	2.0×10^{-25}
3μ	-179	1.6×10^{-18}	-185	3.2×10^{-19}	-207	2.0×10^{-21}	-237	2.0×10^{-24}
6μ	-166	2.5×10^{-17}	-172	6.3×10^{-18}	-194	4.0×10^{-20}	-224	4.0×10^{-23}
10μ	-150	1.0×10^{-15}	-156	2.5×10^{-16}	-178	1.6×10^{-18}	-208	1.6×10^{-21}

The above power levels illustrate the potential vulnerability of optical sensors to saturation or nondestructive laser effects. Although LEL might not have sufficient intensity on target to damage an FPA, even small commercially available lasers can cause saturation. For example, the ideal far-field intensity S (W/m^2) of a laser is given by

$$S\left(\frac{W}{m2}\right) = \frac{PD^2}{\pi\lambda^2 z^2}$$

Where P (W/m^2) is source power, D (m) is the diameter of aperture, z (m) is the distance from the source, and λ (m) is the wavelength.[39] Calculations of a few notional laser sources are shown in table 4.

Although the actual laser intensity on target would be less due to scattering, absorption and non-ideal diffraction, table 4 shows that even low-energy lasers could produce intensities greater than 200 dB above the intensity of the desired signal. The result is that FPA-based optical sensors would be saturated beyond their ability to properly sense light, rendering them totally unable to perform their intended function.

Table 4. Ratio of laser intensity to desired signal intensity at specified distance.

Type	λ(nm)	Power (W)	Aperture (mm)	Intensity at target (W/m^2)	Gain of laser to desired signal
handheld	532	0.5	1.5	1120 @ 25 km	5.6×10^{24}
Industrial diode	532	100	1.5	223.4 @ 800 km	1.12×10^{27}
Industrial CO_2	1060	5,000,000 (peak)	25	2.3×10^9 @ 25 km	1.44×10^{27}
Industrial CO_2	1060	60 (average)	25	2.7×10^4 @ 25 km	1.69×10^{22}

Threat

Will potential adversaries possess LELs capable of denying and degrading FPA sensors in the 2030–2040 timeframe? Industrialized nations will certainly have the technical capability. Russia has been conducting research into high-energy military lasers since the 1960s, and possesses the tracking and operational capability to employ LEL in a disruptive role. China will also have this capability, and has perhaps already employed ground-based lasers against US satellites, possibly in a laser ranging role but maybe with the intent to degrade US space-based imaging sensors.[40] Iran could develop a counterair and counterspace LEL capability as a byproduct of its self reliance on arms production, nascent

space and intercontinental ballistic missile program, and potential use of lasers to produce highly enriched uranium. Additionally, many industrialized nations will produce high quality commercial lasers which meet or exceed the specifications of LELs as described above. There is a high probability that a determined actor could build on high technology exports from these nations in order to militarize a LEL capability by 2030.

In particular, one should note the aforementioned scenario of autonomous RPAs operating in the near space regime. These vehicles will have a long-duration, quasistationary loiter over territories where nonstate actors such as Hezbollah, al-Qaeda, and associated movements, the Revolutionary Armed Forces of Colombia, etc., will operate. Proliferation of LELs to hostile nonstate actors, improvements and cost reductions in optical tracking systems, and technical assistance from a wealthy patron, could render these high-altitude sensors vulnerable to disruption.

In any case, when nonstate actors obtain advanced weapon systems, high-end state actors are often caught unaware and are forced to alter their battle strategies. Examples include the proliferation of shoulder-fired antihelicopter missiles to Islamic militants in Afghanistan during the Soviet-Afghan War and to the warlords in Somalia in 1993, Hezbollah RPA flights over Israel in 2004, explosively formed projectiles

to Iraqi insurgents in 2005, and antiship cruise missiles to Hezbollah in the 2006 Israel-Hezbollah War.[41]

Recommendations

The two recommendations that result from this research are to continue examining the effects of lasers on focal plane arrays and to investigate and implement technologies to protect sensitive optical sensors from lasers while enabling their continued use in a laser environment.

Research Effects of Lasers on Focal Plane Arrays

As indicated earlier in this report, the effects of intentional laser radiation on focal plane arrays are not fully understood. While research has shown that even low power lasers can produce temporary and permanent degradations in sensitive optical detectors, the overall military utility of "laser dazzling" is not well characterized. The Air Force should continue research into understanding the parameters of laser effects on FPAs, to include types of damage caused by different types of lasers, pulsed versus continuous, degradation versus destruction, reversible versus nonreversible, and disruptive effects as a function of power. Better understanding of the effects of lasers on FPAs in a battlefield environment will help shape investment decisions for technologies to preserve friendly use of optical sensors.

Research and Implement Protection Technologies

Given the danger that LELs pose to continuous operation of optical sensors, the Air Force should invest in technologies that attenuate or filter lasers while permitting continued viewing, or "look-through." Attenuation and filtering are two technologies that could negate or mitigate the laser threat to sensitive FPA optics.

Many of the historical laser protection techniques involve attenuation of arriving energy to avoid damage. For example, mechanical shutters can be used to close the optical aperture in response to laser irradiation. However, mechanical shutters are undesirable, as they result in successful sensor denial. Additional attenuation techniques include automatic gain control and electro-optic modulators, both of which reduce resulting voltages in the detector elements.[42] Laser radiation attenuation gas chambers, which consist of chambers of energy-absorbing gas adjacent to the focal plane array surface, are also being investigated as ways to protect sensitive optics against lasers.[43] Another possibility is the use of carbon nanotube-based optical limiters to provide a broadband limiting response from visible to long-wave IR.[44] Attenuation techniques can protect sensitive circuits against voltage spikes and thermal overload, but could reduce the detector's sensitivity and performance.

Filtering techniques offer another path to achieving maximum sensor performance in a laser environment, as these techniques protect

sensitive FPAs from laser radiation while minimizing reductions in sensor sensitivity and performance. Traditional laser filtering technologies include neutral density filters, optical interference filters, and semiconductor attenuators.[45] Modern spatial and adaptive filtering techniques, however, offer additional possibilities. Spatial filters, which use coherent light and diffraction characteristics to remove random fluctuations from the intensity profile of arriving light, are now implemented as digital signal processing algorithms due to improvements in processing speed.[46] Digitally implemented spatial filters are standard features in typical FPA technologies, including both CCD and complementary metal oxide semiconductor devices.[47] Additionally, adaptive filters are an advanced field of mathematics, electronics engineering, and physics which could be useful in filtering unwanted laser interference from the desired target signals. Adaptive filters, such as matched filters, spectral factorization, and subspace methods, are designed to self adjust a transform function to conform to continuously changing background characteristics.[48] Although adaptive filters have historically been employed in acoustic (e.g., noise cancellation and sonar) and radio-frequency environments, improvements in electro-optic and signal processing technology may lend their application to adaptive optical filtering. Multispectral FPAs can be designed with in-band laser detectors, which disable a finite spectrum region but enable continued processing of the remaining EO/IR spectrum.

Although both attenuation and filtering technologies have merit for preserving friendly use of optical sensors in a laser environment, it is not practical to choose a single technology which would be best in all circumstances. Therefore, the Air Force should state the requirement to implement technologies to negate or mitigate laser effects on focal plane array-based optical sensors, while continuing to investigate optimal solutions.

Conclusion

The US Air Force, other military services, and other government agencies, will field a wide variety of RPAs by 2030. Most will be equipped with focal plane array-based optical sensors in the ultraviolet, visible, and infrared spectrum. Low-energy lasers pose a denial and degradation threat to these sensors. Industrialized nation-states will likely possess laser-countermeasure capabilities in the 2030–2040 timeframe, capable of preventing use of blue-force optical sensors. Nonstate actors will likely possess some form of LEL, but could have difficulty engaging highly maneuverable near earth vehicle-based sensors. However, even nonstate actors should be able to deny optical sensors on near space platforms. Improvements in commercial astronomy, laser communications, adaptive optics, and other industrial applications will improve non state actor capabilities to employ LEL. The Air Force should state requirements for continued optical sensor operations in a laser environment, and should implement this protection in all future optical sensor arrays intended for

near space platforms (as a threshold) and for all remaining platforms (as an objective). The Air Force should also continue research on the disruptive effects of laser radiation on FPAs and the most cost effective way of attenuating or filtering in-band lasers while preserving the remainder of the spectrum for friendly use.

Notes

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