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Technical Paper

MYTH OR REALITY?

HIGH-ENERGY LASERS ARE FAIR-WEATHER WEAPONS

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EXECUTIVE SUMMARY

Warfighters need to know that the weapons at their disposal are going to function as expected, when needed. As newer and more advanced kinetic and non-kinetic weapons are introduced into the warfighter's repertoire, there's a pressing need to understand how and when those weapons should be used to greatest effect.

Which brings us to the question:
Are high-energy lasers (HELs) only "fair-weather" weapons?

HELs can cause physical damage to targets like small boats, munitions, or drones from the ground or from the air. Because lasers allow for pinpoint accuracy in targeting, they can greatly limit collateral damage. And since the energy travels at the speed of light, a target cannot evade an accurately aimed HEL beam. Moreover, it can be difficult to detect. But for an HEL to work properly, it must hit the target with accuracy and the desired amount of energy.

But what if there's less than ideal weather? How does that affect the functioning of an HEL?

The ability to focus a laser down to a small spot size with sufficient power density at a desirable range can be challenging in certain external conditions such as thermal blooming, atmospheric turbulence, and atmospheric extinction. The HEL weapon community has been actively working to mitigate the effects of these conditions for many years, and in the case of atmospheric turbulence, has made significant advances using adaptive optics.

When looked at as a whole, the complexity of these factors calls for tools to be developed that will assist warfighters with understanding, in real-time, the effectiveness of the HEL weapons they are provided.

It's worth noting that while we advance the effective use of HELs in multiple atmospheric conditions, they can also serve another very important function—improving situational awareness. In one example, the U.S. Navy placed an HEL weapon on the U.S.S. Ponce, where in addition to its capability as a weapon, it was used almost continuously as a Cassegrain reflecting telescope with an infrared camera that allowed visibility of distances greater than 10 kilometers and penetrating things like smoke, haze, and even light fog.

Booz Allen engineers and scientists have been at the forefront of Directed Energy (DE) and are helping the Department of Defense develop and operationalize DE weapons like HELs. These technologies offer the potential to provide cost-effective precision attack or enhanced point defense, in addition to other flexible non-kinetic uses.

HIGH-ENERGY LASERS: A BLOWTORCH AT A DISTANCE

The author, David Stoudt, prefaces this article on a highly complex subject with the answer to the question: "Are High-Energy Lasers Fair-Weather Weapons?" No, not with modern technology and weaponeering tools.

There are complexities surrounding the use of high-energy laser (HEL) weapons and the need for the technical HEL community to develop *tactical decision aids* (TDAs) for the effective use of these weapons by warfighters on the battlefield. The fundamental purpose of these TDAs is to drive complexity out of the HEL-engagement kill-chain to reduce the burden on the already overtaxed military battle staffs.

Some of the basic "kill" mechanisms for HEL engagements of targets include (1) heating a structural component to failure, as is the case for pressurized tanks; (2) structurally penetrating the target to take out critical subsystems; and (3) elevating the temperature of energetics within a target to initiate a detonation or deflagration. In all three of these kill mechanisms, the effect of the HEL weapon can be summarized as a "blowtorch at a distance," or in other words, the kill mechanisms rely on the deposition of energy per unit area on the surface of the target [Joules/cm^2].

In a perfect world, all the photons leaving the exit aperture of an HEL would be focused into a tight spot on the target and would exceed the threshold energy density for the desired effect. Thus, a 100-kW continuous-wave (CW) laser that is focused down to an 8-cm diameter spot size (or "bucket") on the target would be delivering a peak irradiance of 2 kW/cm^2 during the engagement. **Figure 1** shows the results of such a laser spot on a 1/8-inch-thick 4"x4" piece of steel (shown laying on a wooden desk), when illuminated for about 2 seconds with a laser wavelength of 1.064 μm.

When studying the impact of HEL irradiation on targets, *material irradiance curves* are often developed, as shown in **Figure 2**.

For metal target materials, one often sees an exponential decrease in penetration times as a function of peak irradiance. It is also important to realize that the penetration time increases exponentially toward a threshold irradiance value, below which, the laser will have minimal impact on the target and the laser magazine would be wasted. The operator needs to know when the incident irradiance on the target is reaching this value, so he or she knows when *not* to fire the laser weapon.

Figure 1: Steel Irradiated with 2 kW/cm^2 for 2 Seconds

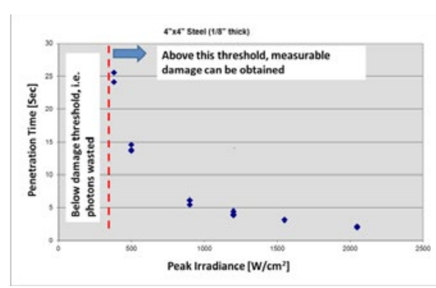

Figure 2: Material Irradiance Curve for 1/8-Inch-Thick Steel

REALITY OF HIGH-ENERGY LASER ATMOSPHERIC PROPAGATION

While the results of laser irradiation of steel are impressive in the above example, the ability to focus a laser down to a small spot size with sufficient power density, at a desirable range from the laser weapon, is challenged by several physical processes that occur in the atmosphere. In particular, *extinction* (which is a combination of absorption and scattering by atmospheric gaseous molecules, aerosols, and water droplets) and *turbulence* (considered to be primarily the result of convective air motion, vertical temperature differences, and wind shear) must be carefully considered. A third effect, which normally comes into play at very high-power densities, is called *thermal blooming*, and is the result of absorption heating the atmosphere that causes a corresponding reduction in the local index of refraction.

Depending on the engagement range and the atmospheric conditions, it might not be possible to employ a laser at all, especially in adverse conditions including heavy rain, very thick fog, or dense smoke. The effects of turbulence and extinction are shown in Figure 3, for the case of a Gaussian beam profile at the exit aperture of the laser as it propagates toward the target.

As you can see, if uncorrected, turbulence will tend to break up the beam profile and result in the beam spreading out, the creation of hot spots (also called *scintillation*), and a decrease in the average irradiance on the target. Extinction, on the other hand, tends not to spread out the beam, but it reduces the overall peak irradiance of the laser as photons are either absorbed or scattered out of the beam. As is further discussed below, **the answer on whether to use a laser weapon is not binary, and while the effectiveness of a laser weapon is negatively impacted by less-than-ideal atmospheric conditions, an HEL can still remain a highly effective weapon in the inventory.**

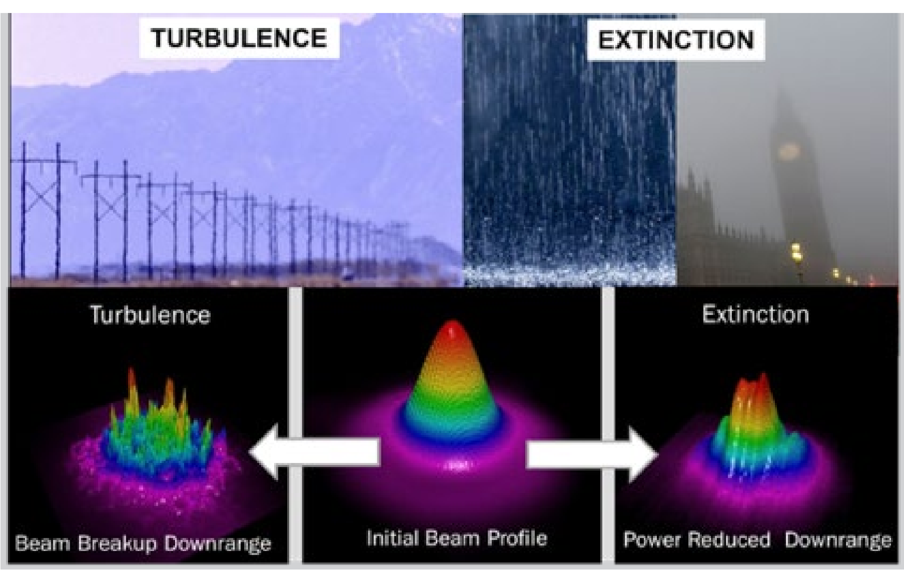

Figure 3: Turbulence and Extinction Effects on a Gaussian Beam Profile

THERMAL BLOOMING

The discussion in the previous paragraph can be somewhat disheartening if your desire is to field a capable HEL weapon that warfighters will be able to employ in more than clear and calm atmospheric conditions. It is important to keep in mind that the HEL weapon community has been aware of these atmospheric effects for decades, and has been actively working to mitigate their effects. More recently, the free-space optical communications community finds themselves faced with the very same challenges (with the possible exception of thermal blooming) and are also working very hard to overcome these obstacles.

In this section, we discuss the important problem of steady-state whole-beam blooming effects with wind or beam motion. Thermal blooming describes a non-linear phenomenon in which propagating laser light deposits a small portion of its energy along the beam path into the local atmosphere. As the laser energy is absorbed by the molecules and aerosols in the air, the ambient air temperature increases, creating localized gradients in air density, and subsequently altering the refractive index of the medium. Figure 4 shows a qualitative sketch of a CW laser beam propagating in an absorbing medium, such as a horizontal path in the atmosphere, where the absorption and cross-wind speed are uniform.

As the air moves across the beam, the temperature increases due to the absorbed energy from the laser beam. This causes the density of the air and also the refractive index (which is proportional to the density) to decrease as the air moves across the beam. The temperature and refractive index

variations across the beam, centered along the wind direction, are shown in Figure 4. Since light rays bend in the direction of increasing refractive index, the central ray is shown in the sketch to be bending into the wind. The net result is that the irradiance profile becomes distorted with its peak shifted into the wind (Gebhardt, 1990).

In general, the beam distortion from thermal blooming of the laser beam results in an irradiance pattern taking the form of a crescent shape, which is illustrated in **Figure 5** (Fussman, 2014). The wind is moving from left to right in the figure, and the bloomed intensity pattern shows the characteristic crescent shape with beam spreading transverse to the wind and the peak intensity shifted into the wind.

The color map indicates the irradiance of the laser beam, with the dark red color representing the highest irradiance and the dark blue representing the lowest. The scale of beam deflection depends upon the distance to the target, beam power, atmospheric extinction, and other parameters.

Keep in mind that, for the thermal blooming discussion above, only a very small percentage of the laser energy is absorbed by the atmosphere. It is the thermal effect of that energy on the atmospheric index of refraction that creates the effect. Thus, most of the energy is still in the beam; it's just not focused where you would like it to be. Gebhardt discusses the process where, for limited atmospheric conditions and engagement geometries, phase correction can be very effective in correcting for thermal blooming when the laser beam quality is very good, or in other words, when the Strehl ratio [1] approaches unity.

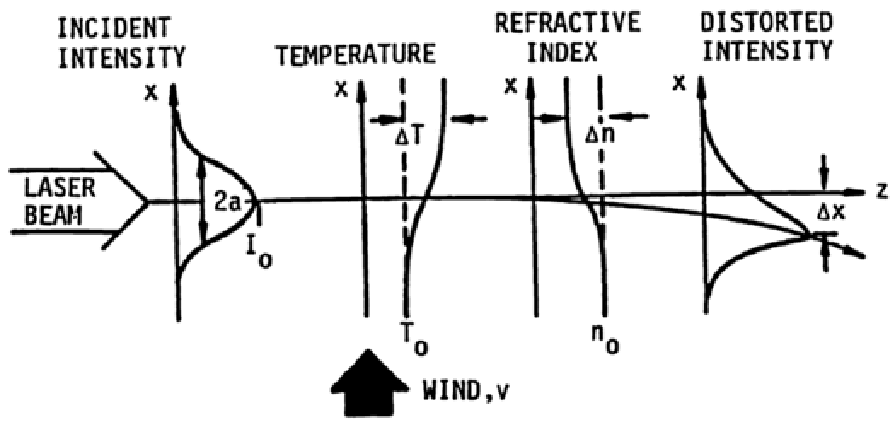

Figure 4: Sketch of Steady-State Thermal Blooming Problem with Wind

Compensation for thermal blooming relies on the same principles of adaptive optics used for the compensation of atmospheric turbulence, which will be discussed further in the next section. **Figure 6** illustrates the characteristic dependence of, in the presence of thermal blooming, peak far-field irradiance [I_{peak}] on the transmitted laser power [P]. When thermal blooming is present, and uncorrected, the curve exhibits a maximum irradiance [I_{crit}], at which point further increases in laser power result in decreasing irradiance on the intended target (Schonfeld, n.d.). When corrective techniques are used, a higher maximum intensity can be obtained on the target.

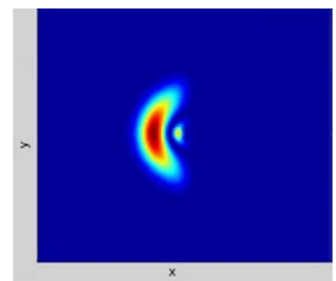

Figure 5: Characteristic "Crescent Shape" of a Laser Beam Experiencing Thermal Booming

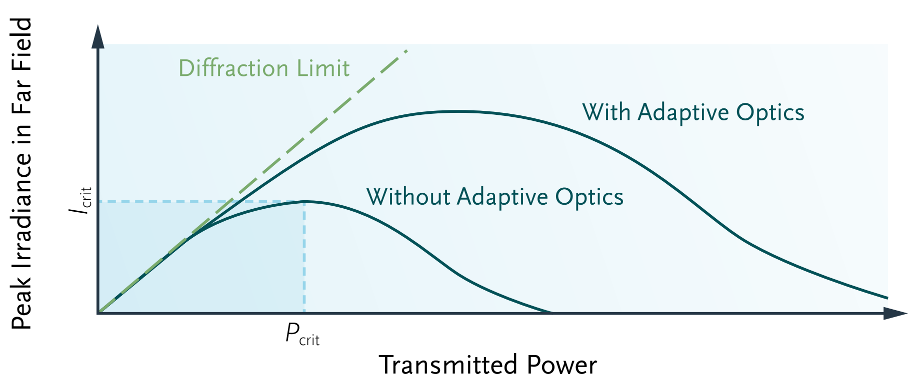

Figure 6: Schematic Behavior of the Peak Irradiance in the Far Field of a Laser Beam Subjected to Thermal Blooming

[1] The Strehl ratio is a measure of the quality of optical image formation, and is frequently defined as the ratio of the peak aberrated image intensity from a point source compared to the maximum attainable intensity using an ideal optical system limited only by diffraction over the system's aperture.

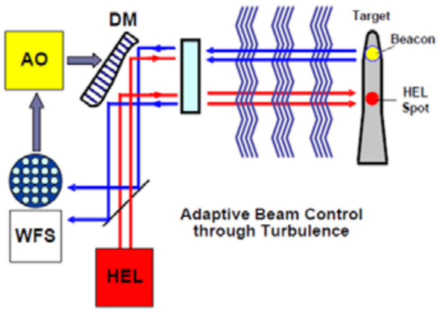

Figure 7: Diagram of an HEL Weapon with a Beacon Illuminator as Part of an Adaptive Optics (AO) System

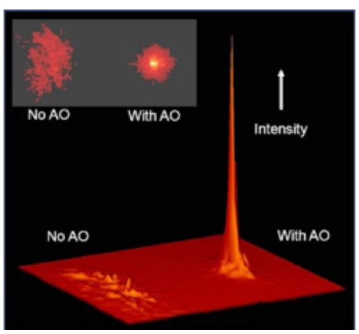

Figure 8: Impact of AO on the Intensity Profile of a Point Source

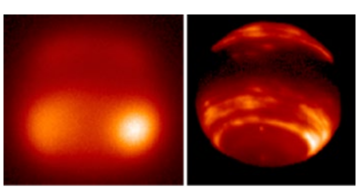

Figure 9: Images from the Keck Observatory of the Planet Neptune Both Without and with AO

The engagement geometry also plays a critical part in determining the significance of thermal blooming on the laser system's ability to create the desired effects on the target. The worst-case HEL engagement scenario is point-defense against a radially inbound target. It this case, the laser beam is not moving appreciably and atmospheric thermal effects are maximized. Fortunately, in most cases of interest, the target flight trajectory results in the laser beam moving through the atmosphere, and thus, thermal effects do not have as significant an impact on those laser engagements.

ATMOSPHERIC TURBULENCE

As stated earlier, turbulence is primarily the result of convective air motion, vertical temperature differences, and wind shear, unlike thermal blooming, which ultimately depends on how energy is absorbed by the atmosphere. The major effects of turbulence on HEL propagation stem from the spatial and temporal fluctuations in the refractive index of air, created primarily by thermally generated randomly varying eddies. The resulting refractive index variations cause different parts of the laser beam to experience different effective path lengths as the beam propagates, which changes the relative phase of portions of the beam and disrupts the coherent focusing of the beam on the target. This effect can cause the beam to spread out and/or break up into beamlets (i.e., scintillate), as shown in Figure 3.

As stated previously, turbulence results in wavefront errors across the laser beam as it travels to the target, which result in constructive and destructive interference and thus scintillation. The drive to understand this effect on laser propagation, both for HEL weapons and optical communications, lead to the development of methods for correcting those wavefront errors; namely, *adaptive optics* (AO). Figure 7 shows a "conventional" AO system that incorporates a Hartmann wavefront sensor (WFS) that measures the reference wavefront of a beacon laser reflected from the target, and a deformable mirror (DM) that applies in real-time the inverse of the sensed aberrations (i.e., the conjugate phase) to the outgoing HEL beam to compensate for aberrations that it would experience on the way to the target.

Therefore, ideally, you would be able to obtain a nearly diffraction-limited beam profile on the surface of the target. When looking at Figure 3, AO would have the ability to basically reverse the beam breakup shown on the left side of the figure, and return the beam profile back to a Gaussian profile, as shown in the center of the figure. The impact of the ability to focus on a point source is illustrated in Figure 8 (Wildi, n.d.).

While AO was developed by the Department of Defense (DoD) to improve the propagation of high-energy lasers and to improve space-situational awareness, the astronomical community benefited by this technology in a very significant way. Figure 9 shows the striking impact that AO had on the ability of the University of California at Los Angeles W.M. Keck Observatory on the top of Mauna Kea Summit, Big Island, Hawaii, to image the planet Neptune with its large segmented telescope.

These same principles of AO hold for correcting the impact of atmospheric turbulence on the propagation of a laser beam to a target.

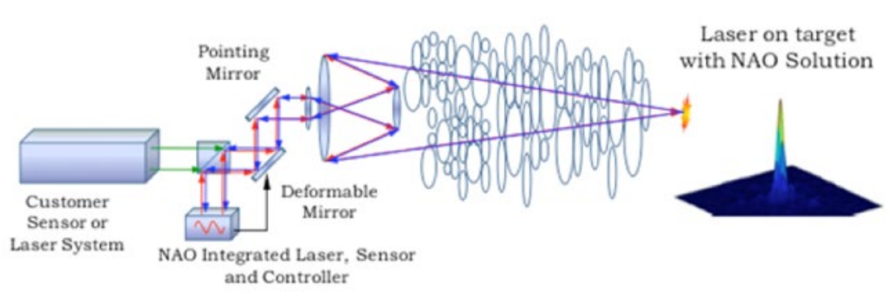

Figure 10: Nutronics AO Scheme Utilizing Their Developmental NAO Technology for Deep Turbulence Applications

The optics community is not standing still when it comes to developing new and more effective ways to implement AO in HEL weapons, optical communications, and astronomy. For example, companies like MZA continue to make improvements to their high-power DMs, and as shown in Figure 10, the company Nutronics is pushing the state-of-the-art by developing new, cost-effective techniques for AO to be used in highly (or "deep") turbulent atmospheres, as is often found in the maritime environment.

Conventional AO has historically been used to correct moderate-to-light turbulence, rather than some of the more challenging deep turbulence applications. The bottom line is that AO systems are getting better, cheaper, and more effective all the time. Challenges remain, but in the near future, AO will likely be able to compensate for both turbulence, and to some degree, thermal blooming, simultaneously.

ATMOSPHERIC EXTINCTION

Molecules and aerosols suspended in the atmosphere absorb and scatter propagating laser energy as it travels to reach the target. Absorption occurs when laser photons transfer their energy to these constituents, resulting in heating of the local atmosphere. Scattering occurs when incident photons are redirected from the beam by atmospheric molecules and particulates. It is the combination of absorption and scattering that is referred to as *atmospheric extinction*. These combined effects are illustrated by Beer's Law in Equation 1, which describes the transmission of light through a linear medium, given as:

$$P(z) = P_O e^{-\in z} \quad (1)$$

where P(z) represents the total power delivered to the target located a distance z from the source, and P_o is the initial output power at the beam director. The variable $\in$ represents the total *extinction coefficient* due to atmospheric absorption and scattering, and is further described by Equation 2 as:

$$\in = \alpha + \beta \quad (2)$$

where, α refers to the absorption coefficient and β refers to the scattering coefficient, each having multiple contributors. Therefore, as the extinction coefficient increases, either by enhanced absorption or scattering, the attenuation of the laser light by the atmosphere goes up exponentially. The result is a reduction of laser irradiance on the intended target. Therefore, understanding the current environment surrounding the HEL weapon—and the degree to which the laser beam will be scattered or absorbed—is critical to understanding the expected irradiance on a target and the required duration of the HEL engagement.

ABSORPTION

The near-IR spectral region is affected by strong absorptions due to molecules in the Earth's atmosphere, particularly water and carbon dioxide. Figure 11 illustrates the strong wavelength-dependent impact that absorption of these molecules has on the transmittance of the atmosphere (Clark, 1999).

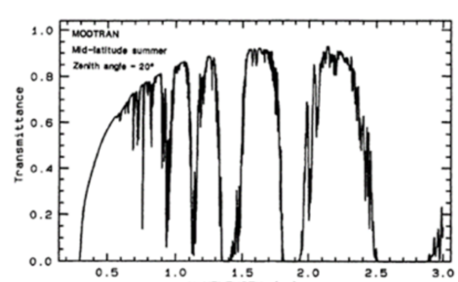

Figure 11: MODTRAN® Modeled Atmospheric Transmittance, Visible to Near-Infrared Wavelengths

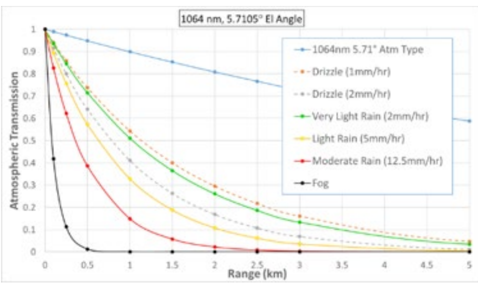

Figure 12: Atmospheric Transmission as a Function of Range to the Target for Various Weather Conditions (Calculations by Lee Schanwald, Booz Allen Hamilton)

Transmittance is typically defined as ratio ($P(z)/P_o$) from Equation 1. Fortunately, the absorption at the most common HEL wavelength, 1.064 μm, is fairly low for the case of water vapor in the atmosphere. Operating in these illustrated so-called *atmospheric windows* is critical for HEL weapons, as well as optical communications.

SCATTERING

The degree and direction that light is scattered in the atmosphere is highly dependent on the relative size (δ) of the scattering aerosol or molecule, compared to the wavelength (λ) of the laser. For the case of molecular scattering, where $\delta \ll \lambda$, an optical phenomenon known as *Rayleigh scattering*, in which shorter wavelengths of electromagnetic energy are scattered much more readily than longer wavelengths, the degree to which light is scattered varies proportionately to the wavelength of laser as [$\propto \lambda$-4].

Typically, photons scattered by molecules have the same wavelength as the incident photons; only their direction of propagation changes. This principle readily describes the phenomenon of the blue daytime sky and red sunsets. Because blue light more readily undergoes molecular scattering than red light, the daytime sky appears blue. At sunset, the path length of light from the setting sun to the viewer through the atmosphere is longer, and by the time the light reaches the viewer's eyes, most of the shorter wavelength light has been scattered, leaving only the longer wavelength red light (Liou, 2002).

For most HEL wavelengths, aerosol sizes are typically on the order of an optical wavelength ($\delta \approx \lambda$). For this dimension of scattering aerosols, Mie theory suggests that the particles scatter and absorb electromagnetic energy in a manner weakly dependent on the wavelength of light passing through them; the degree to which light is scattered varies proportionately to the wavelength of laser as [$\propto \lambda^{-1.6 \text{ to } 0}$] (Van de Hulst, 1957). Dust, pollen, pollutants, smoke, and microscopic water droplets that form haze, moderate-to-light fog (or mist), and clouds are common causes of Mie scattering. Mie scattering occurs mostly in the lower portions of the atmosphere, where larger particles are more abundant, and dominates in cloudy conditions. Mie scattering by dense fogs is by far and away the most serious impediment to long distance laser engagements with attenuations that can exceed 300 dB/km, as compared to a typical microwave maximum attenuation of 10 dB/km due to rain (rain drops are Mie scatterers at microwave frequencies) (Smyth, et al., 1995).

The third generalized scattering regime occurs when the atmospheric particles are much larger than the laser wavelength ($\delta \gg \lambda$). Scattering in this regime is called geometric or non-selective scattering where the angular distribution of scattered radiation can be described by geometric optics. Rain drops, snow, hail, cloud droplets, and heavy fogs will geometrically scatter laser light. The scattering is called non-selective because there is no dependence of the attenuation coefficient on laser wavelength (Wallace & Hobbs, 1977). Because all light is scattered in a similar fashion, this is why clouds are white.

Figure 12 shows the effect of extinction on the propagation of a 1064 nm laser at an elevation angle of 5.7° in the Washington, DC area. The calculations were done using the Air Force Institute of Technology (AFIT), Center for Directed Energy, Modeling and Simulation (M&S) tool LEEDR (Laser Environmental Effects Definition & Reference) for atmospheric attenuation estimates.

The results show that the degree and direction in which light is scattered in the atmosphere is highly dependent on the relative size (δ) of the scattering aerosol or molecule, compared to the wavelength (λ) of the laser. Dense fog clearly has the most significant negative impact. The rain rate in mm/hr is also a critical variable in trying to understand the tactical impact of the effectiveness of an HEL weapon. Figure 12 shows that the impact of the weather is negative, but not binary. There are many situations where having an HEL weapon effective range out to 1 to 2 kilometers is still militarily useful, and depending on the rain rate and the margin between the HEL weapon power and the target lethality threshold, Figure 12 shows that an HEL weapon can remain militarily useful. Figure 12 is only considering extinction, while other factors such as turbulence and target tracking need to be included. When looked at as a whole, the complexity of these factors calls for weaponeering tools to be developed that will assist the operators with understanding, in real-time, the effectiveness of the HEL weapons they have been provided.

Figure 13: Demonstration of How SWIR Sensors Can Offer Better Imaging Through Smoke (Top), Fog (Middle), and Other Atmospheric Obscurants (Bottom) Than Visible Sensors Can

SITUATIONAL AWARENESS

An interesting and significant side benefit from placing an HEL onto any platform, is the greatly enhanced capability for high-quality situational awareness. This was absolutely found to be the case when the U.S. Navy fielded the LaWS HEL weapon on the U.S.S. Ponce (AFSB[I] 15). While the system was only used sparingly as an HEL weapon, it was almost continuously used for enhanced situational awareness. An HEL Beam Director, which, for LaWS, was basically a 60 cm Cassegrain reflecting telescope that was also fitted with a short-wave infrared (SWIR) camera, greatly enhances situational awareness out to >10 km. Figure 13 highlights the advantage of using the longer SWIR wavelengths, typically defined as light in the 0.9–1.7 μm wavelength range, for penetrating through obscurants like smoke from a forest fire (top), haze caused by water vapor (middle), and even pollution (bottom). The images are clearer due to the greatly reduced scatter at the longer wavelengths.

CONCLUSION

What should be very clear in the above cursory treatment of laser atmospheric propagation is that there are many complex interactions taking place with various dependencies on wavelength, power density, weather conditions, location, propagation direction, and others. The dominant interactions discussed were atmospheric turbulence, extinction, and thermal blooming. The science and engineering needed to compensate for turbulence, and (to some degree) thermal blooming, are advancing rapidly and becoming much more cost-effective. For regions where deep turbulence dominates, techniques are still being developed, and the results look promising. In fact, for target engagement ranges of a few kilometers or less, AO is often considered unnecessary.

Regarding extinction, comprised of both absorption and scattering, the environment that the HEL system is being used in will dictate how effective the laser will be. Dense fog is probably the most challenging environment to operate in, and laser effectiveness will be dubious at best. Should this dissuade us from continuing to develop HEL weapons for the warfighter? The answer is a resounding "no." One must keep in mind that the effects of atmospheric perturbations on the operation of an HEL weapon are not binary. In fact, for many combinations of less-than-optimal weather/atmospheric conditions (light rain, haze, dust, etc.), when combined with realistic operational scenarios, the HEL weapon will still provide the warfighter with a preferable capability when compared to currently available kinetic options. Thus, as stated at the beginning of this article, the answer to the title ***is*** in fact "No, not with modern technology and weaponeering tools."

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Figure 1: Photograph used with permission from Dr. Christopher Lloyd and Mr. Bryan Knott, Naval Surface Warfare Center (NSWC) Dahlgren, HEL Lethality Group, 2016.

Figure 2: Graphic used with permission from Dr. Christopher Lloyd and Mr. Bryan Knott, NSWC Dahlgren, HEL Lethality Group, 2016.

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