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The importance of thermal blooming for laser weapon atmospheric propagation modelling

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Abstract: Thermal blooming occurs when a laser is sufficiently intense to modify the properties of the propagation medium via a thermal transfer of energy. It is investigated with a kW-class near-infrared fiber laser over extended ranges.
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1. Introduction

A wide variety of effects comes into play when it comes to atmospheric propagation of HEL beams. The most common ones are diffraction, absorption, aerosol scattering, and atmospheric turbulence, all of which have a linear influence on the propagation of laser beams. However, as the average [1] or peak laser power increases, other nonlinear effects become significant. Thermal blooming is probably the one with the strongest impact on High Energy Lasers (HEL) beam propagation in the atmosphere [2,3]. It stems from transverse density gradients resulting from the absorption of laser energy by molecules and airborne aerosols. As more energy is absorbed, the local temperature increases causing a density depletion and hence a reduction of the refractive index. This gradient acts as a self-induced negative lens that can limit the peak irradiance delivered at long ranges. It can be especially detrimental in situations where the angular sweep of the HEL beam is limited.

Thermal blooming in the atmosphere was studied extensively in the past with CO_2 [4], chemical [5] and free electron lasers [6]. The advent of ruggedized and commercial fiber-based HELs [1], which have been used in a number of demonstrations for military applications, has renewed the interest in atmospheric thermal blooming and the impact it has on the propagation of these lasers in the atmosphere. Moreover, several groups led theoretical endeavors trying to model and simulate the behavior of laser beam experiencing thermal blooming [2,3,7].

In this paper, the nonlinear effect is revisited using a fiber-based near-infrared kW-class laser supported by experimental investigations over extended ranges. The collected data was used to verify and validate the Program Optimized for the Propagation of HEL (PrOP-HEL) developed by Defence Research and Development Canada (DRDC) to assess for the impact of the atmosphere on beam delivery in different conditions.

2. Test facilities

The experiments described were done with DRDC's High Energy Laser mobile laboratory, comprising a kW-class fiber laser from IPG Photonics installed in a 6 m-long mobile trailer connected to a refractive beam expander with a 25 cm output aperture. The beam director is mounted on a pan and tilt to allow for fine positioning of the laser beam on the irradiated sample.

Testing was conducted on two different ranges, each one appropriately equipped to monitor atmospheric conditions in real-time. The first site consists in a 250 m long tunnel allowing laser propagation experiments in controlled environments. As it is not subject to the influence of transverse winds, HEL propagation in the tunnel provides ideal conditions to emulate extended stagnation zones [8].

The second consists in a 2.5 km long outdoor range. The HEL trailer was located at one end while a specially equipped experimental station, located at the other end of the range, was used for beam characterization. A scintillometer monitored the integrated turbulence strength along the propagation path while a weather station recorded all the relevant atmospheric parameters.

3. PrOP-HEL

In order to help predicting the performance of a HEL system in different atmospheric conditions, a modelling platform named PrOP-HEL was created. To increase calculation speed, it was developed around NVIDIA's Cuda framework for GPU calculation. The implemented phenomenology includes diffraction, wavelength-dependent molecular absorption, aerosol scattering, atmospheric turbulence and thermal blooming. The model propagates an initial wavefront defined by its complex amplitude and alters its propagation using phase masks.

The derivation of the phase screens representing thermal blooming is achieved using the hydrodynamic model [2], which takes into account the laser irradiance distribution, wind amplitude, and direction, absorption coefficient of the propagation medium and diffusivity of the heated air in the bulk atmosphere. As the absorption coefficient is typically low, the amount of heat absorbed by the atmosphere produces only small changes of the thermodynamic variables. Under these conditions, the density variation attributed to the additional heat can be determined from the linearized conservation of mass, momentum and energy.

4. Some results

The indoor tunnel is a facility ideal to investigate propagation through extended stagnation zones, in the absence of transverse wind. While such atmospheric conditions may not occur frequently in nature, stagnation zones exhibit extreme blooming behavior and allow for a thorough study of the spatial and temporal dynamics. Figure 1 (a) presents the steady-state irradiance profile intercepted after the laser beam propagated 200 m in the indoor tunnel and 1(b) corresponds to the resulting profile obtained using PrOP-HEL.

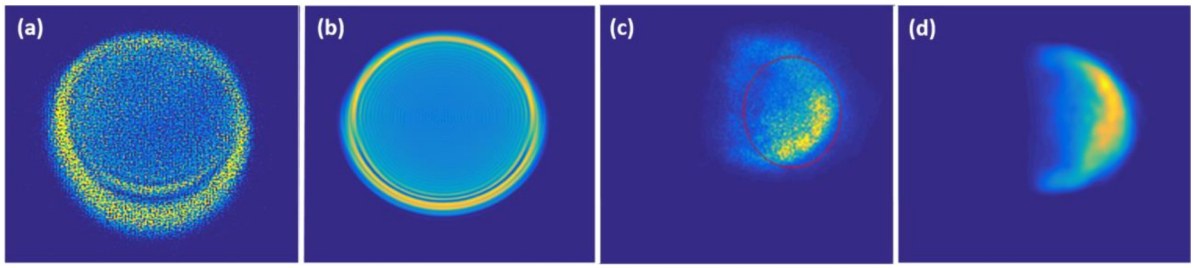

Fig. 1: Beam profiles intercepted after 200 m indoor (a) and 2.5 km outdoor (c) and the corresponding intensity distributions calculated using PrOP-HEL (b, d).

Figure 1(c) was obtained by focusing the laser beam down the 2.5 km long outdoor range during a humid, weak wind day. As suggested by the figure, a transverse wind component moving from the right side of the image to the left, forced the laser energy into a crescent-shaped distribution characteristic of the presence of thermal blooming. This behavior was also reproduced using PrOP-HEL and shown in Figure 1(d).

5. Conclusion

While interesting from a fundamental research perspective, the study of thermal blooming is essential for the development of operational concepts dictating the use of laser weapons. Modelling tools such as PrOP-HEL will facilitate the development of concepts of operation adapted to specific scenarios. For example, the thermal blooming impacts on the lethality will influence positioning of the weapon system on the battlefield to avoid situations where the laser beam propagates through stagnation zones. Finally, the risk of 'target spillover' attributed to thermal blooming can limit possible firing arcs due to increased hazards to airborne objects along the beam trajectory.

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