Electro-Optic Propagation Through Highly Aberrant Media

A Thesis submitted to the University of Adelaide as a requirement for the degree of Doctorate of Philosophy in Mechanical Engineering

by

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Preface

This document is the culmination of many years of study, and is the thesis submitted for the award of Doctoral of Philosophy. The topic of research is electro-optic propagation through highly aberrant media. The effect of a high temperature, high turbulence gas medium on the propagation of various laser beams is studied. The propagated beams are imaged using focal plane array cameras and the images analysed to determine spatial and temporal degradations. The work importantly supports the laser beam defense of aircraft. A better understanding of laser beam propagation through high temperature and turbulence regimes was needed to provide better assessment of the capability of on-board laser systems (DIRCM) to defend aircraft from infrared seeking missile attack when scenarios dictate that the laser beam must propagate through the jet engine exhaust gases. The work improves the understanding of laser beam propagation in high temperature and turbulence regions, thereby allowing better optimization of the operation and design of life-saving DIRCM systems.

Abstract

Infrared guided, or “heat seeking” missiles, have posed a threat to aircraft ever since their inception. However, the proliferation of man portable shoulder launching infrared guided missiles has increased the threat level against both military and civilian aircraft. Furthermore, advanced variants of the missiles are less susceptible to decoy against traditional countermeasures such as flares. To counter the threat, advances in laser technology have allowed the development of small, robust and powerful infrared lasers that have been developed into laser defence systems that can be fitted to aircraft. These systems, Directed InfraRed CounterMeasures (DIRCM), detect the incoming missile and direct modulated infrared energy, in the form of a laser beam, on to the missile sensor to disrupt the missile’s guidance.

The defence system works well in laboratory settings, and through normal atmosphere, but effects of a highly aberrant propagation path on the laser beam’s temporal and spatial quality need to be considered. In particular, scenarios may arise where the laser beam must pass through the hot, turbulent gases of the engine exhaust, the plume. Some initial system studies highlight the problem but have not reported on the individual effects of the various laser and flow parameters in this high temperature, high turbulence environment. Furthermore, laser beam propagation has traditionally been studied at atmospheric temperatures and often in the visible spectrum to support geodesy.

The thesis incorporates a system level study in collaboration with the Defence Science Technology Organisation, Australia, and the Defence Science and Technology Laboratories, UK. The study showed general properties of the propagation but did not allow detailed analysis of the effect of the various flow and beam parameters on the laser beam propagation.

To further contribute to the knowledge in this field, the thesis took a novel approach to the study of laser beam propagation by using an experimental apparatus to produce high temperature, high turbulent flows in the laboratory for the purpose of studying the laser beam degradation while controlling flow and beam parameters. This approach allowed the individual effects of flow and beam parameters; such as turbulence intensity, eddy scales, species concentration, wavelength, beam diameter and temperature, to be isolated analysed.

High temperature turbulent flows were generated by combusting a lean mixture of hydrogen and air, while applying perforated plates of various hole diameters and blockage ratios to the jet nozzle to condition the flow. The resulting flow was traversed by 632.8 nm and 4.67 µm wavelength laser beams of varying beam diameter. The resultant laser beam was recorded using visible and infrared detecting focal plane array cameras. The temporal and spatial properties of the propagated beams were analysed and linked to the flow conditions. The flow was characterised in terms of integral length scale and turbulence intensity using Particle Image Velocimetry (PIV) as the diagnostic tool.

The study found temperature, eddy size, beam diameter and wavelength to be parameters that significantly affected the laser beam propagation. For example, the beam displacement, for both wavelengths, was found to increase as the beam diameter was decreased, closely following the inverse third root of the beam diameter. Further, there was a difference in beam displacement related to wavelength. It was found that the 632.8 nm beam would need to be 8/7ths times greater in diameter than the 4.67 µm beam to produce the same beam displacement variance.

The experiment has extended the data range used to develop existing models and has allowed correlations to be observed at the higher temperatures found typically in jet engine plumes. These results show existing models that link beam diameter and wavelength to beam displacement at these higher temperatures are still valid.

The role of path length, although seen to be significant, was not able to be quantified using the experimental set-up, while the presence of carbon dioxide was found through theory and measurement to not be significant at the wavelengths studied.

A significant finding of the work has been the quantifying of the effects of high temperature on laser beam propagation. New data has provided correlations between beam displacement and temperature. The change in the increase in beam displacement variance with high temperature was found to be related to the inverse square of temperature. Beam displacement variance tended towards an asymptote at around 600°C for both wavelengths studied. However it was notable that the beam displacement variance was found to be related to wavelength, with the visible beam exhibiting a notably greater variance than the infrared beam at temperatures above 400°C. The new correlations have shown beam displacement models need to represent the effects of wavelength. This is required for the displacement variance to be correctly modelled as the temperatures increase to levels found in a jet engine plume.

Measurements also showed that as temperature increased, mean and variance of the spot size and the irradiance variance all increased. This data is reported in the thesis and can be used to estimate the energy being directed onto the sensor of an incoming missile under various flow conditions.

The findings and approach presented in this thesis has meant the impact of hot turbulent exhaust flows on the propagation of the DIRCM laser beam can be confidently predicted under a range of conditions. These results provide certainty for those designing DIRCM systems.

Declaration

NAME: William Martin Isterling PROGRAM: PhD

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