

JATE

Journal of Aviation Technology and Engineering 4:2 (2015) 49–54

Measuring the Effectiveness of Photoresponsive Nanocomposite Coatings on Aircraft Windshields to Mitigate Laser Intensity

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Abstract

In 2004, pilots reported 46 laser illumination events to the Federal Aviation Administration (FAA), with the number increasing to approximately 3,600 in 2011. Since that time, the number of reported laser incidents has ranged from 3,500 to 4,000. Previous studies indicate the potential for flight crewmember distraction from bright laser light being introduced to the cockpit. Compositional variations of the photoresponsive nanocomposite coatings were applied to an aircraft windshield using a modified liquid dispersion/heating curing process. The attenuating effects of the deposited films on laser light intensity were evaluated using an optical power meter and the resultant laser intensity data through treated and untreated windshields was collected. Data revealed a reduction in laser intensity (36–88%) in the presence of the engineered photoresponsive nanocomposite films. Results lend support of the view that the addition of transparent laser attenuating films applied to aircraft windshields may improve flight safety, and reduce the risk from distraction or disruption of flight crewmembers' vision.

Keywords: laser, illumination, aviation, aircraft, hazards, photoresponsive, nanocomposite, security, coating, safety

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Introduction

Representatives of the aviation community are interested in mitigating the effects of flight deck laser illuminations. For this study, the researchers defined a laser illumination as both the intentional and unintentional use of a laser beam penetrating an aircraft windshield during any phase of flight or ground operation. The Federal Aviation Administration's (FAA) Laser Safety Initiative indicated a nine-fold increase in laser incidents between the years 2006 and 2012 (FAA, 2012). According to DeMik et al. (2013), a visible laser beam illuminating the windshield may cause temporary flash blindness, glare, or distraction. Laser visual interference effects may be a hazard during critical phases of flight, such as approach and landing, takeoff, and emergency maneuvers.

One of the earliest reports of lasers being utilized to distract pilots was during the Falkland/Malvinas conflict in 1982 (Anderberg, Bring, & Wolbarsht, 1992). The British Royal Navy used laser systems to distract and temporarily blind Argentine pilots engaging in attacks on British naval vessels. In the same report, American pilots were also said to have been the target of laser attacks from the Soviet Union's *Sovremny* class destroyers during the Cold War. Laser attacks continue to be problematic for military operations where pilots in conflict areas are subjected to deliberate attacks. In contrast to military operations, civilian aircraft in United States airspace are primarily concerned with illuminations caused by persons not knowing or caring that bright laser light can distract and disrupt flight operations. In an FBI (2014) press release, they disclosed 3,960 FAA-reported laser illuminations in the United States alone in 2013, a dramatic increase from the 384 incidents reported in 2006.

In 2012, the FAA launched a laser safety initiative intended to increase awareness and also work with federal, state, and local law enforcement agencies to pursue civil and criminal penalties against individuals who purposely aim lasers at aircraft. On February 14, 2012, the President signed Public Law 112-95, known as the FAA Modernization and Reform Act of 2012. Section 311 amended Title 18 of the United States Code Chapter 2, section 39, by adding section 39a, which makes it a federal crime to aim a laser pointer at an aircraft (FAA Modernization and Reform Act of 2012).

Advancements in laser illumination protection may provide solutions to reduce the intensities of laser light illuminations. Early attempts at reducing laser intensity have included various forms of protective eyewear or visors. It was determined that these alternatives were not ideal for a variety of reasons. Some of these devices did not allow enough light to pass through to the eye, which is especially important during night flight (Murphy, 2009; Svec, 2005). Eyewear designed to attenuate or block certain colors also may unsafely attenuate or block the same colors in cockpit instruments or airport lighting. In one case, aircrew wearing yellow visors attempted "... to land on an unusable portion

of the runway, and they were unable to see the large yellow 'X' indicating the hazard" (Svec, 2005, p. 42). Additionally, these devices require special care, must be safely stored to prevent damage, and require pilots to perform an additional action to those required for flight operations.

In a study conducted by DeMik et al. (2013), laser intensity was measured through multiple flight deck windshields using various laser wavelengths, laser outputs, and ranges. The study determined that relatively low-powered lasers had measured intensity levels through cockpit windshields that may impede safe operations during critical phases of flight. Recommendations from this study include alternatives to protect against the effects of laser intensity in the flight deck. In a continuation of this effort, the departments of Aviation and Transportation, Chemistry, and Physics at Lewis University in Romeoville, Illinois collaborated on a study to develop a practical and economical solution through the use of photoresponsive nanocomposite coatings on aircraft windshields.

The FAA (2004) adopted exposure limits established by the American National Standard (ANSI Z136) and the Laser Safety Hazards Committee (SAE G10T). These limits are enforced at the federal level by the Food and Drug Administration's (FDA) Center for Devices and Radiological Health (CDRH). The four categories of exposure limits are Nominal Ocular Hazard Distance (NOHD), Sensitive Zone Exposure Distance (SZED), Critical Zone Exposure Distance (CZED), and "Laser-Free" Exposure Distance (LFED). The NOHD is reported as an irradiance level at or beyond 2.54 mW/cm² where the beam could possibly result in eye injury. The SZED is reported as an irradiance level from 0.1 mW/cm² where the beam could possibly cause flash blindness. The CZED is reported as an irradiance level from 0.005 mW/cm² where the beam could possibly cause glare. The LFED is reported as an irradiance level from 0.00005 mW/cm² where the beam could possibly cause flight crew distraction. Table 1 outlines the exposure limits. For further explanation of the exposure effect terms, Murphy (2009) explains the term "temporary flash blindness" as being similar to a camera flash, with the potential for after images to exist. Glare makes it difficult for the pilot to see the environment outside and night vision begins to dissipate. Distraction is defined as "an unexpected laser or bright light that can distract the pilot during a nighttime landing or takeoff. He or she might not immediately realize what was happening. Also, the pilot

Table 1
FAA Advisory Circular 70-1 laser exposure limits.

Exposure Limit	Ocular Effect	Power/Unit Area mW/cm ²
NOHD	Possible Eye Damage	2.54
SZED	Flash Blindness	0.1
CZED	Glare	0.005
LFED	Distraction	0.00005

may be worried that a brighter light or other threat would be coming” (p. 3).

For these reasons, this study sought a mitigation method where normal flight activities would not be obstructed, yet the effects of the laser could be lessened, if not eliminated completely. This study focused on testing the application of various photoselective coatings to aircraft windscreens in order to mitigate the effects of laser exposure to crewmembers. The Chemistry Department developed the photoselective coatings, and the Physics Department developed an apparatus to efficiently test the coatings while allowing safe viewing of laser illumination. Researchers bench-tested the coatings in a laboratory prior to conducting field tests at the 200- and 500-foot distances.

Statement of the Problem

In 2013, DeMik et al. determined that laser intensities may impede safe operations during critical phases of flight. This study focused on testing the application of various photoselective coatings to aircraft windscreens in order to mitigate laser exposure to crewmembers. This study attempted to answer the following research questions:

1. What is the resultant measured intensity of laser light penetrating the flight deck based on laser wavelength, laser power output, distance from the laser to the windscreen, and coating concentration?
2. How do the measured intensities compare to federally mandated eye safety requirements (established by the ANSI Z136 Committee and enforced at the federal level by the FDA’s Center for Devices and Radiological Health—CDRH)?

Methodology

Windscreens

The windscreens used for this phase of testing were formerly used on a Boeing 737, next-generation aircraft and were donated by Southwest Airlines. Each windscreen consists of a PPG 112 Aerospace vinyl layer sandwiched between two thermally tempered glass panes, and is approximately 1.25 inches thick (PPG Aerospace Transparencies, 2012).

Lasers

Lasers utilized for this study were classified as FDA IIIb devices and are typical of those used in laser light shows, research, and industrial applications (FDA, 2014). One device used for this study was a custom-built, doubled Neodymium-Doped Yttrium Aluminum Garnet (Nd:YAG) green laser at a wavelength of 532 nanometers (nm) with approximately 20 milliwatts (mW) of continuous wave

(CW) power. The second device used was a blue diode laser at a wavelength of 447 nm with 20 mW of power.

Coatings

The synthetic design of the photoresponsive coatings are based on nanoparticle scintillator materials deposited into a thin transparent polymeric matrix. A scintillator is a material which re-emits absorbed radiation energy in the form of light (Blasse, 1994). Scintillator materials can be treated with an organic “capping ligand” to chemically modify the response mechanism, which results in an increased absorption of laser light. This work employed the use of a cadmium sulfide (CdS) quantum dot nanoparticles as the photon capture source that were anchored to a titanium dioxide (TiO₂) core particle. To this system an additional organic ligand was added to aid in the capture of laser light at the desired wavelengths.

The nanocomposite material was dispersed into a polyvinyl alcohol (PVA) solution that would serve as the final polymeric matrix. Coatings were applied in liquid form directly onto the windscreen, and after partial drying, the dispersion was exposed to heat, which would cure the polymeric matrix onto the windscreen surface (Figure 1). The first coating contained only PVA, was colorless, and was the approximate thickness of a contact lens. This coating served as a control for the study and contained no nanocomposite (a concentration of zero). Coatings A, B, and C also consisted of PVA, but contained variations of the photoresponsive nanocomposite (coating A had the lowest concentration, while C had the highest).

Laboratory Measurements

Researchers used a Newport 918D-SL-OD2R detector with a Newport 1918-R power meter to measure laser intensity with a reported calibration uncertainty of $\pm 1\%$ in the range of 400–940 nanometers. For laboratory bench testing, an apparatus was designed to obtain measurements in a

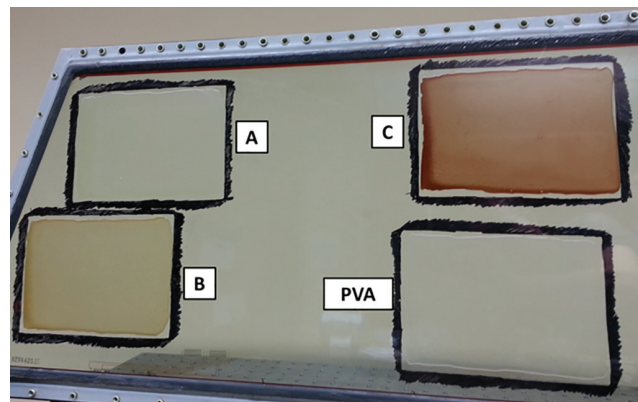


Figure 1. Coatings applied to the 737 windscreen.

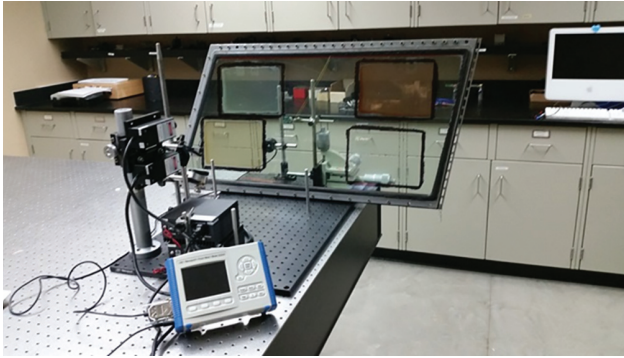


Figure 2. Laboratory bench test apparatus.

controlled environment that mimics field tests (Figure 2). The coatings were applied to the windscreen and then tested at a short range with no artificial attenuation on the beam. Absorbance values were determined by finding average beam intensity through the windscreen alone and through the various applied coatings.

Field Testing Procedures

Windscreens for the study were then treated with the four different coating concentrations. Readings were collected outdoors at a varsity soccer and outdoor track facility in an area closed to the public. The field provided a level and enclosed area at an elevation of 679 feet above mean sea level. Lasers were set up on the east end of the track and projected toward the western border of the fabric-covered fence. Testing began after sunset to minimize signal-to-noise issues caused by external light sources such as sunlight. Field tests were performed at ranges of 200 and 500 feet. These ranges were selected for this study based on the findings of DeMik et al. (2013), which found that the highest potential hazards from laser illuminations occurred at the closer distances of 200 and 500 feet. All researchers were equipped with certified safety laser eyewear rated for protection from the lasers utilized in this study. The glasses effectively protected the eyes of the wearer, but made it difficult to view the location of the laser beam. The laser was directed at the ground and was incrementally moved toward the detector utilizing a portable industry grade optical breadboard and precision targeting components. Once the beam was targeted directly at the detector, the first baseline measurement was obtained demonstrating laser intensity through the windscreen alone. The second reading was taken through the PVA coating, with the third, fourth, and fifth measurements being taken through coatings A, B, and C. Each set of readings was taken at both the 200- and 500-foot ranges, and then the process was repeated with the second laser. Twenty total readings were taken for the study.

Results

The first research question was constructed to determine the resultant measured intensity of laser light penetrating the cockpit after passing through a laser attenuating coating based on laser wavelength, laser power output, and distance from the laser to the windscreen. Figures 3 and 4 report the measured power (mW/cm^2) of light through the windscreen and the coatings from each laser at the 200- and 500-foot distances.

DeMik et al. (2013) measured the increase in beam diameter with distance and the associated decrease in power density. While this phenomenon is well understood for diffraction limited beams, it is more complicated for some of the diode laser sources that were also used in this study. As the nanoparticle concentrations increased, the intensity of both lasers decreased at the aforementioned ranges consistent with the previous work by DeMik et al. (2013).

The main factor of interest in this study was the reduction in measured intensity of laser illuminations through the application of various photoselective coatings to aircraft windscreens. Upon examination of the data (Figure 5), it appeared that there were meaningful reductions in laser intensity through all coatings ranging from 36–88%.

The second research question was constructed to determine whether the measured intensities exceeded federally established eye safety levels when measured through uncoated as well as measured through the various coatings applied to the flight deck windscreen with the lasers used in this study. Upon examination of the data, none of the readings at either the 200-foot distance or the 500-foot distance exceeded the NOHD exposure limit ($2.54 \text{ mW}/\text{cm}^2$) that could possibly result in eye damage. Data revealed that at the 200-foot distance all results for both lasers through the uncoated windscreen were at or above the level for SZED ($0.1 \text{ mW}/\text{cm}^2$) that could result in flash blindness. However, this hazard effect appeared to diminish through all films. When comparing the uncoated windscreen to Film C at the 500-foot distance for both the blue and green lasers, data revealed the most positive result in reducing the hazard effect from flash blindness to either glare or distraction.

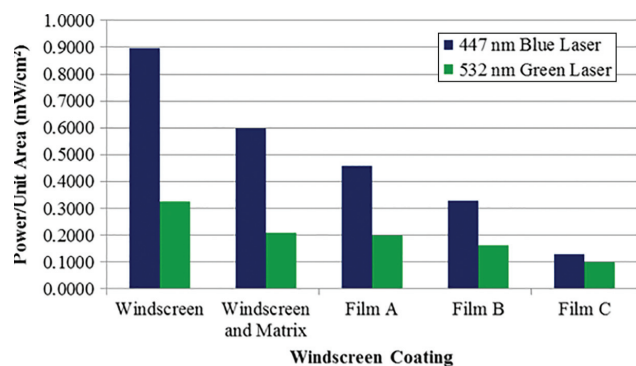


Figure 3. Effects of films on laser power at 200 feet.

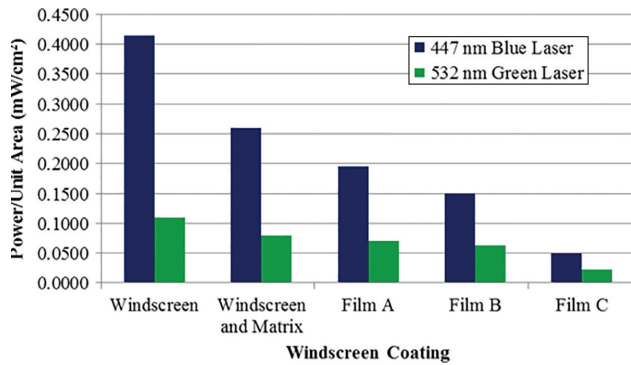


Figure 4. Effects of films on laser power at 500 feet.

Discussion of the Results

The purpose of this study was to test the application of various photoresponsive nanocomposite coatings to aircraft windscreens in order to mitigate laser exposure to crew members. Findings suggest a reduction in laser intensity through all coatings, with both lasers, at all ranges. To give one example, with the 20 mW green or blue laser used, a pilot flying at a distance of 500 feet from the laser may have his or her hazard effect reduced from possible flash blindness to glare or distraction by the application of Film Coating C. There was a meaningful reduction in laser intensity when tested through the coatings utilized in this study. It is also noteworthy to mention that the majority of laser illuminations occur within the critical flight zone as defined by the FAA that represent distances well beyond 500 feet (Nakagawara, Montgomery, & Wood, 2011). This study was conducted at ranges well inside of these distances, and they represent a worst-case laser illumination scenario.

The results of this study support the view that coatings applied to aircraft windscreens may improve flight safety.

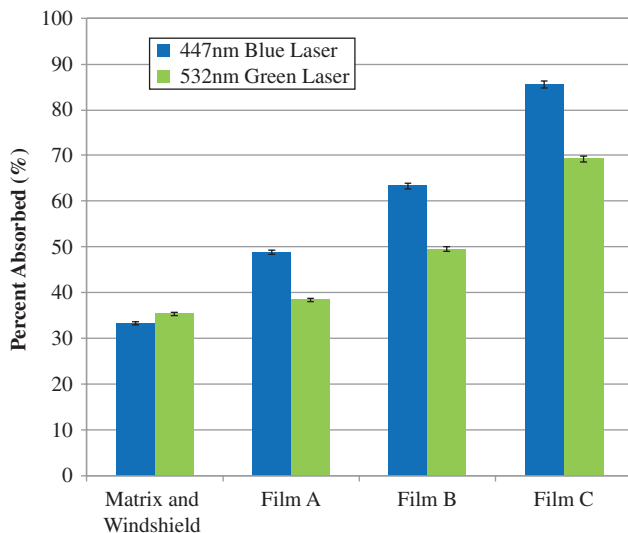


Figure 5. Effects of films on absorbance.

Based on the results of this study, the potential risk of eye damage or visual interference during illumination events may be reduced with the application of photoselective coatings. Since laser illumination events are on the rise, the concept of coating application may serve as a solution to minimize the adverse effects of laser illuminations. In terms of specific reductions in laser intensity through coating application, the results of this study are unique in that the researchers provide an initial data point to support the application of photoselective coatings.

Recommendations for Future Research

As the threat of laser illuminations is relevant to aviation safety, further research is needed to reduce these hazards. This study supports the concept that the application of photoresponsive nanocomposite coatings may reduce the intensity of laser illumination incidents. Additional research should be conducted regarding the formulations of nanoparticle coatings to seek continued improvement and effectiveness of further reducing laser light intensity. Further testing is needed to measure the tint and potential effects of a pilot's visual acuity and ability to recognize colors in the flight environment when photoselective coatings are utilized. Additional testing is also needed regarding the impact of environmental factors on the coatings, along with the longevity and durability of these coatings in the flight environment. Variables should include extreme temperature fluctuations both from internal (windscreen heat) and external (atmospheric) sources, ultraviolet (UV) exposure, and other external elements. Additional research is also needed regarding applying the appropriate method of laser mitigation to the flight deck environment. For example, should active means, such as placing protective eyewear be utilized, over passive means, such as applying coatings to the aircraft windscreens?

Safe flight operations depend on the ability of pilots to function without distractions in a complex and highly critical flight environment. As the number of laser illuminations continues to be problematic, reducing the threat of laser incidents can be improved by researching new technologies.

Acknowledgements

This research was sponsored, in part, by a grant from the Colonel Stephan S. and Lyla Doherty Center for Aviation and Health Research.

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