Safety Science 110 (2018) 178–191

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

How are laser attacks encountered in commercial aviation? A hazard analysis based on systems theory

Daniela Schmid[a,*], Neville A. Stanton[b]

[a] Institute of Flight Guidance, German Aerospace Center (DLR), Lilienthalplatz 7, 38108 Braunschweig, Germany
[b] Human Factors Engineering, Transportation Research Group, Civil, Maritime and Environmental Engineering and Science Unit, Faculty of Engineering and the Environment, Boldrewood Innovation Campus, University of Southampton, Burgess Road, SO16 7QF, UK

ARTICLE INFO

Keywords:
Laser illumination
Aviation
STAMP
STPA
Systems theory

ABSTRACT

Laser attacks in commercial aviation have become headline news worldwide and the frequency of incidents has increased. A review of the research regarding lasers in commercial aviation shows the need for a systematic analysis. By applying a hazard analysis of system theory (both STAMP and STPA) to a practical example it is possible to identify countermeasures and their current state of elaboration. Furthermore, this research considered the concept of reduced-crew operations, and the possible effects of laser strikes. Whereas the pilot operational procedures are established, the legislation lags behind for some nation states. Detection and prevention of lasers operating in the same area as aircraft is critical reduction of attacks.

1. Introduction

Over the last two decades, the increased number of laser attacks at aircraft has become a growing concern in civil aviation (Civil Air Navigation Services Organisation, 2014; Esler, 2016; Eurocontrol, 2016). The aviation community had already recognized lasers as a flight safety hazard around the turn of the millennium (Nakagawara & Montgomery, 2001; Rash & Manning, 2001; Stastny & Griffith, 2001). Fig. 1 shows the calculated ratio of reported laser attacks to annual flight movements for each country in the left chart. There had been an increasing trend of laser attacks in air traffic up to 2010. Since then, the laser attacks' trend has decreased slightly except in Australia and USA. Against this background, the total number of laser attacks has remained constant since 2015 as shown in the chart on the right side. Until the middle of the last decade, none of these laser incidents in aviation was linked to terrorism (Elias, 2005). No commercial airliner has been involved in a laser-related crash yet. Nonetheless, laser illuminations become more and more critical for flight safety because they can be used as weapon as well in terms of global trends in terrorism. Laser light aimed at an aircraft cockpit can illuminate the crew and distract the pilots during critical flight phases at low altitudes. This is especially the case for single-pilot aircraft, where a laser attack on approach can become extremely hazardous. In civil aviation, commercial aircraft are most likely to be illuminated by a laser beam from ground (Nakagawara et al., 2010). More than 73% of reported incidents of a laser illumination stem from commercial carriers in US during 2004–2008. Most occurred under an altitude of 10,000 feet. Here, approach (45%) and final approach (24%) were affected most whereas departure (7.9%), enroute (7.8%) and descent (5.3%) were affected much less. During these low-level flight operations, the pilots' ability to operate the aircraft is impaired, particularly for laser illuminations above 5 μW/cm^2 (Nakagawara et al., 2003). In addition, the flight operations in these phases are characterized by high workload which does not tolerate any limitations on eyesight (European Commission, 2015). During approach, the pilot and copilot have to complete many tasks with strict safety margins (Federal Aviation Administration, 2001). Here, any distraction by lasers or any other source is hazardous for safe flight operations. These exemplary US-American data on the frequency of laser incidents need be supplemented with international statistics because there are no complete datasets for international regions yet.

The following incident on a Boeing 737-8AS represents a typical example of a laser strike and its effects on flight operations. In this incident, the scheduled passenger flight from Lille (France) to Porto (Portugal) had proceeded uneventfully until the aircrew was conducting a final non-precision approach during twilight (Air Accident Investigation Unit [AAIU], 2016). The First Officer (FO) as Pilot Flying (PF) recognized a laser light from the city centre, which did not shine into the direction of the aircraft, before disappearing. He did not inform the Captain because he assumed the beam had been switched off. Suddenly a laser light glared into the cockpit. The FO protected his eyes

* Corresponding author at: Deutsches Zentrum fuer Luft- und Raumfahrt e.V. (DLR), Institute of Flight Guidance, Lilienthalplatz 7, 38108 Braunschweig, Germany.
E-mail address: daniela.schmid@dlr.de (D. Schmid).

https://doi.org/10.1016/j.ssci.2018.08.012
Received 24 January 2018; Received in revised form 14 August 2018; Accepted 15 August 2018
0925-7535/

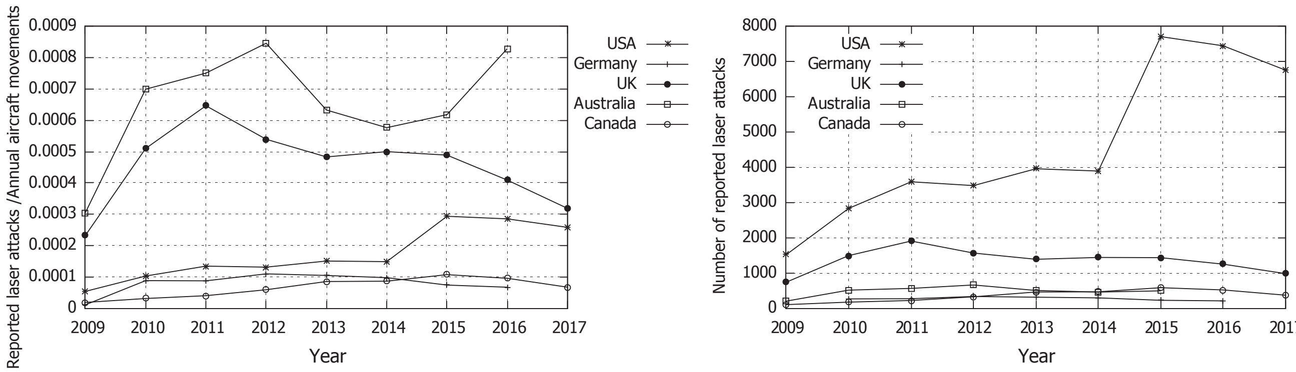

Fig. 1. The occurrence of reported laser attacks measured by annual air traffic compared with the total number of laser attacks per state.

by putting the left hand up in front of his eyes. The Captain as Pilot Monitoring (PM) did not recognize the laser, looked up, and the laser hit her eyes. As a result, she suffered from flash-blindness and missed the "approaching descent" call. She simultaneously confirmed the Air Traffic Control's (ATC's) instruction to contact the tower frequency and informed approach control about the laser strike. The FO announced "approaching descent" himself and carried out corresponding actions. As the aircraft had been above the ideal flight profile (because of the missed approach descent call) it returned to its original descent path by increasing speed and rate of descent. In the meantime, the Captain's (PM's) flash-blindness was over, she was aware of the FO's (PF's) actions, and confirmed the "approaching descent" actions as completed. The FO (PF) requested the extension of landing gear and flaps to reduce the increased aircraft speed. The approach had become unstable due to an increased speed which is why the Captain (PM) requested a missed approach procedure. The FO (PF) executed the procedure and subsequently landed the aircraft safely. The Captain did not suffer any lasting injury. Incidents such as this example of a laser strike are extremely hazardous to flight operations because laser beams can cause harm to the pilots' sight and affect their ability to operate the aircraft. Hence, the present work considers how these laser attacks on commercial aircraft may be counteracted.

A laser (*Light Amplification by Stimulated Emission of Radiation*) device produces "an intense, coherent, directional beam of optical radiation by stimulating emission of photons by electronic or molecular transition to lower energy levels" (International Civil Aviation Organization [ICAO], 2017b, p. 5). The classes 1–4 of a laser specify the level of the laser radiation hazard in standardised viewing condition (International Electrotechnical Commission, 2014). The higher the class the more dangerous is the given laser beam of a device for the human eye. Visible lasers as of class 2 and above can cause a temporary visual incapacitation of a pilot. A pilot may be medically fit but is suddenly impaired in their visual ability by the glare of a laser. In this way, a negative physiological state of a pilot could arise (i.e., visual impairment) which might jeopardize flight safety (ICAO, 2012). Lasers can cause four different types of visual distraction and damage of the human eye through the cockpit windshield: distraction, glare, temporary flash-blindness and eye injuries (Murphy, 2009; Nakagawara et al., 2007; Palakkamanil & Fielden, 2015; Wright & Scott, 2016). Firstly, a laser beam can distract the pilot during take-off and landing. It veils vision to a greater extent than light from non-laser sources. Secondly, glare as an intrusive light source can reduce visual activity and contrast sensitivity. In this way, an after-image can remain in the visual field for a few seconds after an exposure to a bright light. Thirdly, flash-blindness potentially knocks out a portion of the visual field as an effect of bright light. The effect persists for a while after the illumination stopped. Finally, a laser beam of all wavelengths can result in eye injuries. For example, a flash-blindness of a commercial pilot may lead to a retinal injury which is an irreversible lesion of a part of the eye and sight (Gosling et al., 2016). Not all effects occur in every case and they can appear alone or in combination with another. Permanent eye injuries are thankfully very rare in commercial aviation (Nakagawara et al., 2008).

The extent to which a laser hazard can subsequently affect the pilot's eyesight is dependent on several factors. In general, the pilot's awareness of outside laser activity is crucial for avoiding all harmful effects of a laser light on vision because they can shield their eyes or look away (Derenski, 2010; Murphy, 2009). If the pilot does not manage to shield his eyes from the laser beam, the following factors can influence the occurrence of visual effects and their appearance to varying degrees. Firstly, the colour of a laser beam directly relates to its wavelength and is less important for causing visual effects. Lasers of all colours, except invisible lasers, can induce glare (ICAO, 2003). During twilight, dawn and night-time, greenish-yellow lasers of 500–600 nm (88%) are hazardous for a possible illumination (Murphy, 2009). Blue and red lasers (ca. 5%) of equal power are less illuminating and less distracting (Nakagawara et al., 2010).

Secondly, the occurrences of laser attacks correlate with natural light (i.e., time of day), day of week, and month (Nakagawara et al., 2011). They are more likely from late summer through early winter between 7 and 11 pm. During summer the total number of illuminations decline to a lower level because of the longer period of daylight. They are more frequent during weekends. In summary, these temporal factors affect the occurrence of laser attacks on an aircraft.

Thirdly, the distance of the laser's source in combination with the power of the laser plays a significant role in determining the extent of its potential damaging effect on pilot's vision. The power of a laser refers to rate with which its energy is emitted (ICAO, 2003). It is measured in watt (joule/second) indicating the amount of optical radiation received in a given period of time. Low powered lasers can damage the eyes from a distance of 200–500 feet (Murphy, 2009). They can cause visual distraction at 1,000–2,000 feet. The laser's power also interacts with the colour of the light band. For example, an illumination of a 5 mW green laser can cause a distraction at 1,200–11,700 feet, a glare/disruption at 260–1,200 feet, a flash-blindness under 260 feet, and an eye damage under 52 feet. A 5mW green laser represents the maximum laser pointer limit in U.S. (Murphy, 2018). The hazard arising from a laser at different distances can be estimated by software, and will depend upon power, divergence and colour band (International Laser Display Association, 2017; Kentek, 2018; Murphy, 2018; Stewart, 2011).

Lastly, beam divergence, motion and speed of aircraft can also play a role in the effects of the laser attack on the pilot's eyesight, but these factors have not been researched as much. For example, a low-divergent beam can be hazardous at greater distances than a high-divergent beam (Murphy, 2009). In other words, a laser beam of equal power is less hazardous to eyesight if its beam is wider. The hazard arising from different divergent laser beams can also be calculated. Operational factors like beam movement or its location relative to the airport are less well understood. A moving laser beam, as used for laser shows, is