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A Monte Carlo approach to evaluate Stray Laser Energy from the F-35 Lightning II

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ABSTRACT

The F-35 Lightning II has a powerful combat laser designator operating at a wavelength and energy levels that are damaging to the human eye at a pulse level. Due to the faceted design of the Electro Optical Targeting System housing, unwanted Stray Laser Energy beams are emitted in uncontrolled directions. These beams are powerful enough to damage the human eye. Care must therefore be taken to ensure that observers on the ground are not unintentionally blinded. Using a general procedure where the hazard distance is determined by the length of the strongest Stray Laser Energy beam in any direction impedes the ability of the Royal Norwegian Air Force to train in Norway due to the size of the firing ranges and the limits to the maneuvering envelope.

We have developed a Monte Carlo based model to determine the hazard "footprint" on the ground for typical flight patterns. The model incorporates several stochastic variables to catch the variations of an execution. The model also incorporates terrain data to evaluate if a beam will hit the actual terrain around a specified target. By running enough instances of the model, it is possible to generate an estimate for the probability of being hit by a beam for ground observers. Analysis has been performed for the unaided eye, binoculars of size 7x50mm and binoculars of size 20x120mm. By evaluating the risk level in accordance with guidelines provided by the The Norwegian Radiation and Nuclear Safety Authority, we have expanded the possibility for training using the combat laser in Norway.

Keywords: Defense, F-35 Lightning II, Operational Analysis

1. INTRODUCTION

Standard airborne laser guided bomb operations require the target to be illuminated by a source. This source can either be located on the aircraft itself or on a secondary illuminator, for example, a ground based laser. The F-35 Lightning II has a powerful laser target designator built into its Electro Optical Targeting System (EOTS) for self-illumination of the target.

A segmented window protects the EOTS, as seen in Figure 1**.** As the laser beam passes through the protective cover, residual reflection from the non-perfect coating creates several Stray Laser Energy (SLE) beams. These SLE-beams are still energetic enough to cause damage to the human eye. The direction of these beams are widely different from the direction of the main laser beam, which is very problematic. This means that even though one has good control of the main laser beam, the SLE-beams can damage bystanders unintentionally.

Figure 1. The segmented window protecting the EOTS system of the F-35 Lightning II.
https://upload.wikimedia.org/wikipedia/commons/1/18/F-35_EOTS.jpeg

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Investigations of a number of methods to eliminate the SLE-beams has unfortunately not led to any solution with adequate performance for both the EOTS and the aerodynamics of the aircraft.

Using standard procedures where you want to eliminate the risk to an individual, it became apparent that training in Norway would not be possible. This is due to the large Nominal Ocular Hazard Distance (NOHD). Using a simple model, which assumes an unknown orientation of the aircraft, and determining the safety distances by taking the largest values of the NOHD as the radius of a sphere around the aircraft, no firing range in Norway is large enough to support training.

This required a new way to evaluate the risk associated with laser operations from aircraft. By analysing the SLE data provided by the manufacturer it is apparent that the worst SLE-beams are above the waterline of the aircraft. This means that they will not intersect the ground. Since the SLE-beams are solely dependent on the azimuth and elevation angle of the main beam, it is possible to do analysis based on an actual operational flight profile.

By doing the analysis based on operational procedures, we can determine a realistic value for the risk based on what the pilot is doing. By modelling enough possible laser runs with stochastic variation, we can build up a statistical representation of the risk.

We have always chosen to be conservative where we can. This is to ensure that the numbers we give for the risk-level have a built in safety factor. One such conservative estimation is that the grid resolution on the ground is larger than the beam-area we are evaluating, but we count the entire resolution cell as a hit.

Since this is a probability-based analysis of the risk of causing eye damage with the SLE-beams, we have used an exposure value that equals five times the Maximum Permissible Exposure (MPE) value given by the guidelines from the International Commission on Non-Ionizing Radiation Protection (ICNIRP). This is because the ICNIRP MPE values contain a large safety-factor, and by taking a 5xMPE value, we are still performing a conservative analysis of the expected damage frequency.

The analysis then take the approach to allow exposures of up to 5xMPE as long as the probability of such an exposure is low. The probability of exposure for values of 5xMPE has to be lower than the accepted risk level defined by Norwegian officials.

2. METHOD DESCRIPTION

The model calculates the safety-footprint using data provided by the manufacturer. They have characterised the system and calculated how the SLE-beams vary with azimuth and elevation for the main beam. Direction in azimuth and elevation and NOHD describes the SLE-beams in the data. The furthest distance at which the SLE-beam can cause damage to a human eye based on MPE defines the NOHD. We have modified these NOHDs based on a 5xMPE threshold instead to get a more realistic analysis as discussed in the introduction.

Several NOHD exist depending on atmospheric conditions and optical aids. We have analysed three NOHDs; for an unaided eye and extended hazard distances for 7x50 and 20x120 magnifying optics. The large magnifying optics are of particular interest, since this is a common size used by plane spotters.

By choosing a target location and knowing the aircraft position and attitude, it is possible to calculate the azimuth and elevation angles for the EOTS. In the model, the aircraft moves along an operational relevant flight path, also known as a run. We model each run as a series of independent points. Each point then represents a possible aircraft position and attitude within operational limits. We incorporate the terrain in the form of Digital Terrain Elevation Data (DTED) to give a realistic evaluation of the safety footprint.

By modelling each point individually, we do not need to enforce a realistic correlation between points. E.g., the aircraft's pitch, yaw and bank angle can all change from -3° to 3° from one step to another, even though this is unrealistic. These attitudes might seem extreme, but we have to assume that these are two possible states for the aircraft during a lasing run.

One execution of the model can evaluate several heights. This means that the safety footprint is valid from a lower to an upper limit if the step resolution is fine enough. The model will run N number of runs per height as selected by the user. The model also accounts for several stochastic variables. These variables either have a normal distribution around a typical value or a uniform distribution, where the operational procedure allows a given variation within specified limits. These variables aim to capture the possible variations in the aircraft attitude throughout a run. These variations occur due to no pilot being able to execute the exact same run twice, as well as incorporating natural variations such as weather.

A typical execution of the model over a relevant set of heights contains around 25000 runs, where each run contains about 350 individual points to evaluate, and each point can have between zero and three SLE-beams that needs evaluation. To handle the large amount of calculations, the model has implemented parallelisation to speed up the execution time. This is straightforward due to the assumed independence of the points within a height-layer.

2.1 Initialisation

First, the user selects a target location by specifying the latitude and longitude. We assume that the EOTS is pointing at this location throughout the entirety of each evaluated run. Given the target location, we can load the DTED-data for a square around the target, ensuring that the square is large enough to capture all SLE-beams that might hit the ground. The DTED-data also gives the height of the target; we then adjust the height of the run to the height above the target.

2.2 Flight Path Generation

The model requires a number of possible flight paths for the evaluation of each height. The flight paths vary to account for different pilot skills and weather conditions. The unclassified flight patterns used in this paper have no operational relevance.

The flight path is a simple box-orbit where we vary three different parameters, the x and y length of the box as well as the distance of the centre of the box to the target. We assume a coordinated 9g turn, and prohibit the laser use during the turn. This eliminates the need to model the turn correctly in six degrees of freedom to get the proper attitude of the aircraft during the turn.

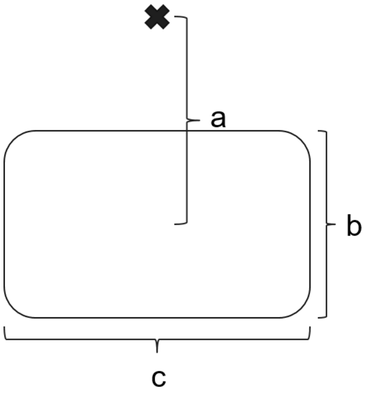

Figure 2. An illustration showing the basics of the box orbit. The three parameters that vary are, a: the distance to centre of box from target, b: the y dimension and c: the x dimension.

The output of the flight path generation is a set of seven parameter vectors; the x and y coordinates at each point throughout the flight path, the aircraft heading at each point, as well as the bearing to the target and the normal distance to the target. We also include a laser toggle, which is just an indication if the laser is on or not. As stated earlier we do not model turns with enough fidelity, so the laser toggle is off during a turn.

Each point of the flight path also gets a pitch, roll and yaw value associated with it. This is to capture variations in aircraft attitude due pilot inconsistencies and weather corrections by the flight control system. These attitude angles translate into azimuth and elevation angles for the EOTS. For example, a positive pitch angle gives a negative elevation angle.

2.3 SLE – evaluation

From the aircraft position and attitude, it is possible to calculate the azimuth and elevation angles of the main laser beam from the aircraft to the target. Using a lookup algorithm, we can now determine all the SLE-beams for that orientation of the main beam. The description of the SLE-beams by their azimuth and elevation angles and the NOHD is not directly usable to investigate where the SLE-beam intersects the ground. We have to transform them from these spherical coordinates to Cartesian coordinates.

After vectorization, the SLE-beam description is by the x, y, and z components in the Cartesian system. Since we now know the aircraft position and attitude, have terrain data in the vicinity of the aircraft, and a Cartesian form of the SLE-beams it is trivial to check if they intersect the ground or not. We filter the vectors by their vertical distance to reduce the amount of computation required. If the vertical distance is short enough, they will never intersect the terrain.

All beams that intersect the terrain populate a mesh. As beams intersect the ground, we build up areas where the potentially damage-inducing exposure has a given frequency or probability under the different conditions evaluated.

3. RESULTS

All data and figures presented in this paper are generated using the box orbit described in section 2.2. The initial analysis showed that only the SLE-beams for the large magnifying optics reach the ground. Footprint plots are therefore only relevant for large magnifying optics. Figure 5 to Figure 7 present this data from the simulations. We also generate a plot that shows how many pulses hit the ground versus height, an example of which is shown in Figure 3.

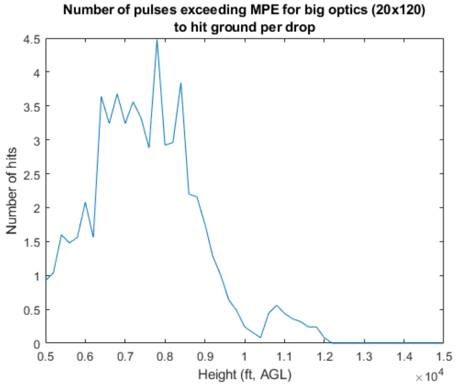

Figure 3. Graph showing how many pulses hit the ground with respect to height for large magnifying optics.

Figure 4 is the actual footprint plot where the target is a lighthouse in the southern part of Norway. The map is loaded from a map-server and is the same size as the DTED data. By making sure all dimensions of our data-matrices match up with the loaded DTED data, it is easy to overlay them to display the results.

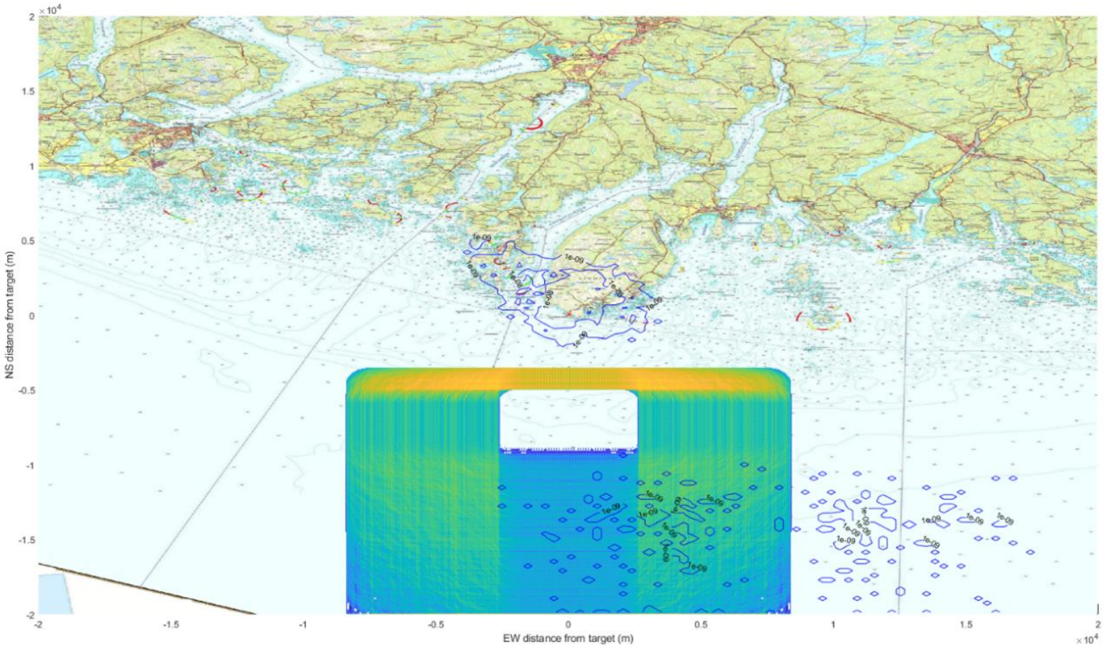

Figure 4. Illustration showing the actual footprint plot generated by the model.

The dark blue contours are the actual footprint with the associated probability of hit by a SLE-beam. The results show that the probability of hit is small, 10^{-9} per run, which is within the accepted risk level of The Norwegian Radiation and Nuclear Safety Authority. The red cross at (0,0) is the target location, and the heat map in the lower half of the figure is a map over the points that have been evaluated. Warmer colors indicate more flight paths through that pixel.

Post-processing the results produce several other figures. These show the SLE-beams mapped out in 3D-space. Figures 5 through 7 show the SLE-beams emitted mainly upwards, it is also clear that only the beams for large magnifying optics intersect the ground.

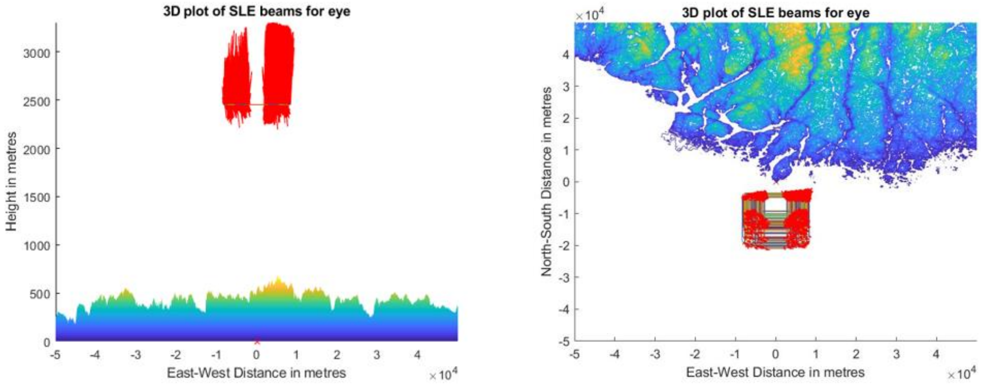

Figure 5. Figure showing how the SLE-beams for the unaided eye map out in 3D space, seen in the y-z and the x-y plane respectively.

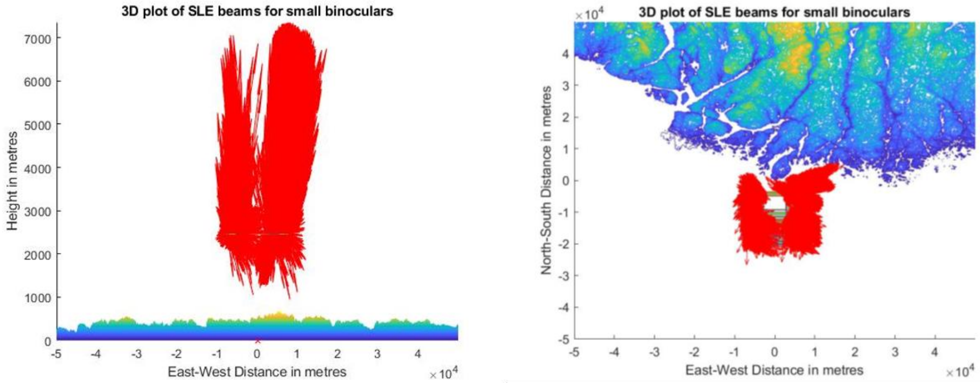

Figure 6. Figure showing how the SLE-beams for small magnifying optics map out in 3D space, seen in the y-z and the x-y plane respectively.

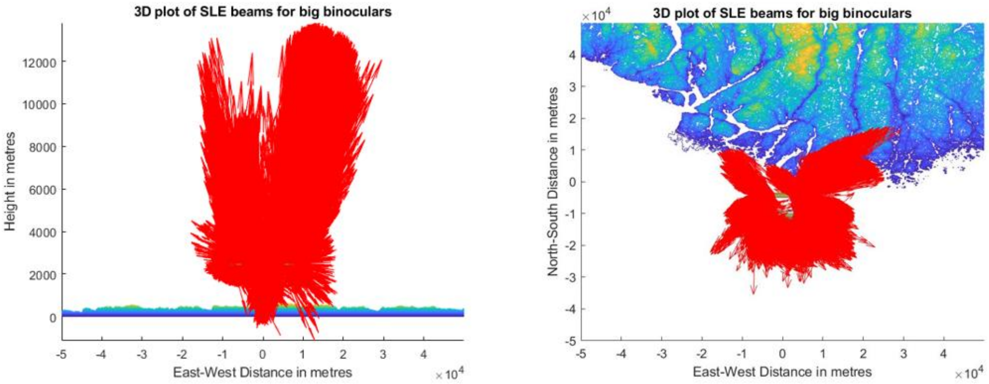

Figure 7. Figure showing how the SLE-beams for large magnifying optics map out in 3D space, seen in the y-z and the x-y plane respectively.

We also create a plot with all the flight paths evaluated, figure 8, as well as a plot showing the actual SLE-hits on the ground. The difference in the actual hits on the ground and the generated contours shows that the contours create a conservative estimate of the actual risk, spanning out a large area round each hit. Figure 9 displays just the area around the target. It can be clearly seen that the SLE-beam hits are very sparse. Comparing this to the zoomed safety footprint in Figure 10, we see that a conservative estimate is given.

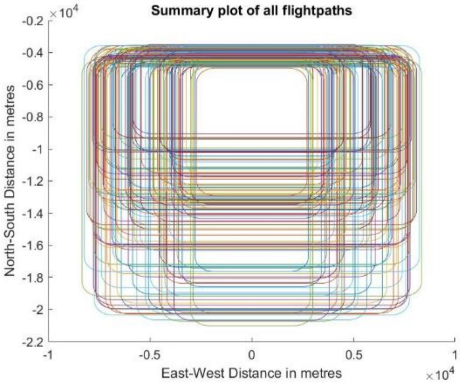

Figure 8. Plot showing all the flight paths evaluated for this run of the model

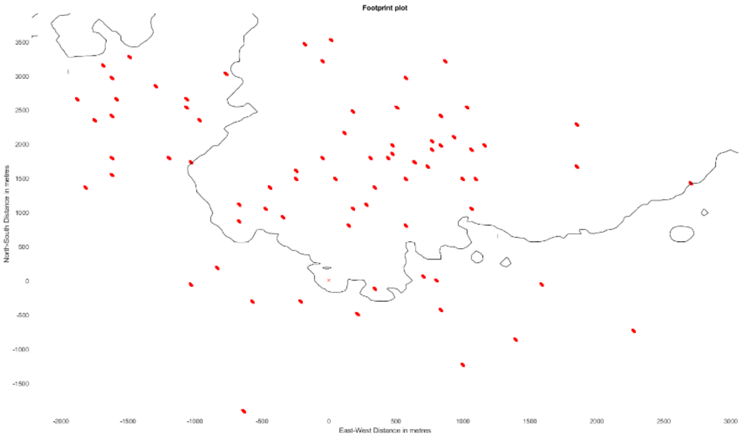

Figure 9. Illustration showing the actual SLE-beam hits around the target

Figure 10. Figure showing the actual safety footprint around the target.

4. CONCLUSION

We have demonstrated a novel way of estimating the risk associated with airborne laser operations. As modern targeting lasers become more powerful, new ways of estimating the risk are required. This is due to the very large safety distances associated with classical methods. By understanding the execution of laser operations, it is possible to tailor the safety analysis. A tailored analysis gives an operational picture of the risk for a ground observer as well as safety distances that allows use of smaller firing ranges for training.