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Monte Carlo Simulation of the Probability of Hazardous Human Exposure from Space Based Lasers

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Abstract

Laser (lidars) used from satellites and space stations for measurement of atmospheric properties may represent an ocular hazard to people on the surface of the earth. For the typical satellite based lidar, the exposure level for the naked eye or with small optical instruments such as binoculars is below the MPE, but for larger telescopes, the MPE can be exceeded. However, for large telescopes, the probability and frequency of exposure are very small due to the small field of view of the instrument and due to the low numbers, respectively. A probabilistic risk analysis model was developed to quantify the risk for ocular injury on the basis of dose-response curves and data on viewing behaviour of various groups using different kind of optical instruments up to an input diameter of 2.5 m.

The probability of receiving an eye injury is a combination of the probability of being exposed and the probability of the incident energy levels of radiation producing eye injury. The risk of an eye injury depends on a range of parameters such as the energy per pulse, wavelength, footprint diameter, atmospheric conditions, and the optical properties of telescopes and other viewing aids. The probability for exposure depends mainly on the viewing behaviour of potentially exposed people. In the probabilistic risk assessment scheme, uncertainties and variabilities of parameters are represented by frequency distributions which are carried through the scheme by way of Monte Carlo simulation.

The results obtained from the risk model can provide input to the Space Agencies to manage ground population risks induced by the application of space based lasers.

1. Scenario Description, Ocular Energy

The scenario is schematically depicted in figure 1. Laser radiation with a given wavelength between the ultraviolet and the far infrared (180 nm – 20 µm) is emitted from the lidar as short pulses (pulse durations less then 1 µs) with a given repetition rate (typically in the order of 10 - 100 Hz) and energy per pulse (in the order of 100 mJ). The laser energy is decreased by wavelength dependent atmospheric scattering and absorption. This is included in the model by transmittance curves calculated with atmospheric model software MODTRAN and FASCODE.

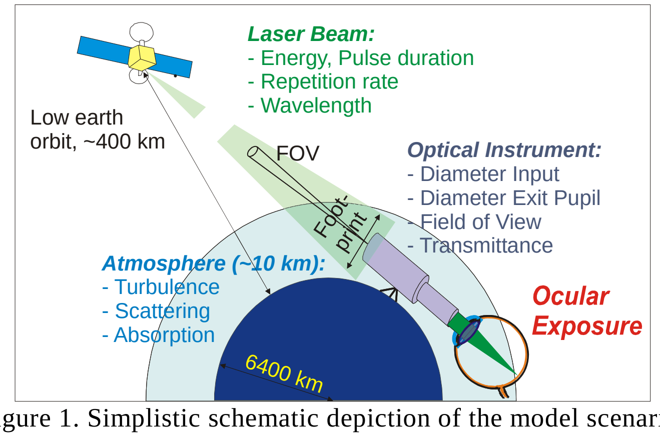

Figure 1. Simplistic schematic depiction of the model scenario.

The beam exposure profile on the earth surface is assumed to be close to a gaussian shape. Scintillation effects which cause a variation of the local exposure around the average value are accounted for using a Beta-Beta distribution [Al-Habash, 1999] as calculated for standard atmospheric scintillation profiles [Churnside, 1993].

The ocular exposure level behind an optical instrument is determined by the diameter of the input optics, the spectral transmittance of the optical instrument and the diameter of the exit pupil. To decrease the range of variation of these parameters, groups of optical instruments are defined in the model, such as binoculars up to 5 cm diameter, and different size-groups of telescopes, up to 2.5 m in diameter. The spectral transmittance T(λ) of a simple telescope eyepiece and of thin samples of glass types often used for lenses in optical instruments was measured and the range of transmittance values for different instrument types with corresponding glass thickness is modelled with a uniform frequency distribution [Schulmeister, 2001a].

All of the above parameters and their distributions produce a frequency distribution of ocular exposure values for each specified group of optical instruments.

2. Population Model

Two different prerequisites are needed for an actual ocular exposure to occur at a given time and location: the laser beam has to be incident at this location and the person at this location has to have the satellite in the field of view, FOV, of the particular optical instrument. This scenario can be quantified by the frequency per hour that a given spot on the earth is illuminated, P_{ill}, and the probability that the lidar-satellite is actually in the field of view of the optical instrument under consideration, P_{FOV}. A combination of the two figures yields the frequency for exposure at a given point on the earth per hour of using a given optical instrument. Typical values for the frequency of illumination of a spot on the surface on the earth are 10^{-4} and 10^{-6} per hour depending on the type of orbit and the latitude.

P_{exp} is the frequency for ocular exposure per hour while using a given type of optical instrument: $P_{exp} = P_{ill} * P_{FOV,}$ where P_{FOV} is a factor from 0 to 1 describing the fraction of time in which the satellite is expected to be in the FOV of the instrument. This number critically depends on the viewing behaviour of the individual for the specific group of observers, the direction of the Line Of Sight of the lidar and the FOV of the instrument. For instance, for general astronomy usage, if it is assumed that telescopes are in the average pointed equally likely in any direction of the hemisphere above 30° elevation, P_{FOV} will be in the range of $7.6 \cdot 10^{-9} – 1.6 \cdot 10^{-3}$ corresponding to minimal and maximal FOV for eye-pieces of 0.01° to 4.6°.

The “activity specific injury rate”, the individual Risk $P_{OD\ ind,}$ of receiving ocular damage per hour of using a given optical instrument, is given by combining the frequency for exposure per hour of using a given instrument with the probability for ocular injury if exposure occurs, P_{OD}. P_{OD} will be further discussed in section 4.

$$P_{OD\ ind} = P_{exp} * P_{OD}$$

In order to calculate the expected number of ocular injuries per mission, the numbers of users of instruments of a given type at a given moment need to be accounted for. The expected frequency of instances of ocular damage per mission hour as a function of latitude degree (for a given group G and latitude Λ) is

$$N_{OD}(\Lambda,G) = P_{OD\ ind}(\Lambda,G) * N(\Lambda,G) * F_{time}(\Lambda,G)$$

where N(Λ,G) is the number of members of a group in a given latitude ring and F_{time} is the fraction of time of usage of optical instrument of given type, such as 1 hour per 24 hours.

Assuming that the groups are exclusive, summations over all latitudes Λ and Groups G give the total expected numbers of humans receiving ocular damage per mission hour

$$N_{OD}(G) = \sum_{\Lambda} N_{OD}(\Lambda,G) \qquad N_{OD} = \sum_{G} N_{OD}(G)$$

Multiplication of N_{OD} with the mission duration yields the distribution for the total expected number of ocular injuries for a given mission given the specified uncertainty distributions.

3. Ocular Damage Model

Severity

Regarding the nature and severity of the consequence, the model is based on the occurrence of a minimal visible lesion, MVL, of the cornea, the lens, or the retina of the human eye. However, the severity of the injury depends not only on the level of the ocular exposure, but also on the location of the lesion, as a lesion in the central part of the retina can result in serious vision loss, but may go unnoticed if located in the periphery of the retina.

Dose-response curve

Due to biological variation and experimentally introduced uncertainties, laser threshold experiments produce a dose-response curve, which, as is generally the case for “response” or “no-response” (quantal response) biological data, can be fitted well by a cumulative log-normal relative frequency distribution for detected lesions [6]. The fit of the data is usually performed according to the “probit” analysis. The median dose, i.e., the dose at which 50 % of the exposures result in a response, is referred to as the “effective dose 50 %”, the “ED-50” (see Figure 2). The second parameter which describes the curve is the slope, defined as the ratio between ED-84 and ED-50 (a slope of “1” would represent a single threshold value with no variability).

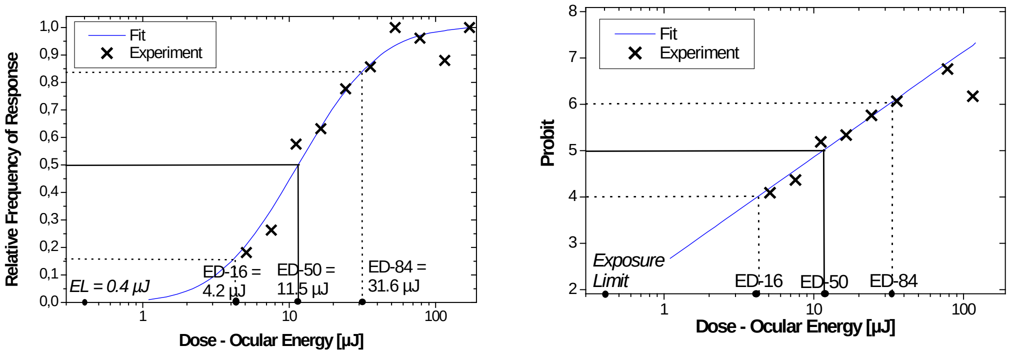

Figure 2. Experimental minimal visible retinal lesion data obtained with short pulsed dye-laser radiation [Lund] is fitted by a cumulative log-normal dose response curve as obtained with probit analysis. Also shown is the laser exposure limit EL for the particular wavelength and pulse duration, which is a factor of 16 below the ED-50.

Previous quantitative probabilistic laser safety studies [8] adopted ED-50 and slope values as reported in the literature and calculated point values for the probability for ocular injury for a given ocular exposure level. However, our analysis of a collection of experimental data showed that the distribution of experimental data results not only from biological variability but also from uncertainties introduced by experimental difficulties, such as achieving a minimal laser spot of 20 µm diameter at the retina of an anaesthetised monkey [Sliney, 2000]. The analysis indicates that thermal and thermoacoustic damage mechanisms apparently have an intrinsic slope of approximately 1.05 to 1.2 [e.g., Bargeron, 1989, Sliney, 1980], whereas much shallower slopes in the range of 1.1 and 2.5 are usually reported for retinal threshold data. Simulations of the impact of difficulties to achieve a minimal image have shown that these increase both the slope and the ED-50 value.

The ocular damage model is based on experimental ED-50 data for wavelengths from 200 nm to 10 µm and pulse durations from 10^{-13} s to 10^{-6} s. It also accounts for experimental uncertainties, which would be absent in a human exposure situation, by defining a frequency distribution for ED-50 values which are reduced in respect to reported experimental values and a correlated distribution for steep "theoretical" slope values [Schulmeister, 2001b].

4. Results and Discussion

The model as described above has been realised on the basis of a standard mathematical software package linked with input and output spreadsheets and plots.

The calculations show, that for typical lidar parameters, exposure to the beam with the naked eye or small optical instruments is harmless and exposure levels are well below international laser exposure limits [IEC, ICNIRP]. However, depending on the energy per pulse, the footprint diameter and the wavelength, large telescopes may be able collect enough energy so that if exposure occurs, an eye injury is likely to result.

The results of sample calculations for three different laser wavelengths but with equal other parameters are summarised in Table 1.

Table 1. Summary of results from sample calculations with parameters: 100 mJ energy per pulse, 50 Hz repetition rate, nadir pointing and 100 m diameter footprint for three different wavelengths, and the lidar being stationed on a dedicated satellite and on the ISS, for a three year mission (at a confidence level of 95 %). In brackets the type of telescopes which are the main risk contributors are given.

Wavelength, main ocular absorption site in brackets	Estimated numbers of ocular injuries, dedicated satellite	Estimated numbers of ocular injuries, ISS
355 nm (lens)	< 10^{-99} (below capabilities of math software)	< 10^{-99} (below capabilities of math software)
532 nm (retinal pigment epithelium)	$6 \cdot 10^{-3}$ (30-60 cm telescopes)	3.3 (60 cm telescopes)
1064 nm (choroid)	$6 \cdot 10^{-6}$ (60 cm telescopes)	$2 \cdot 10^{-2}$ (250 cm telescopes)

The marked difference in risk numbers is due to the much smaller ED-50 values, reflecting a greater sensitivity, for 532 nm in comparison to 1064 nm and 355 nm. For the same energy per pulse and footprint diameter, but with wavelengths of 355 nm, 532 nm and 1064 nm, the ED-50 can be exceeded with telescope diameters of about 2.5 m, 30 cm, and 60 cm, respectively. With decreasing telescope diameter, the expected frequency of ocular exposure strongly increases. The much higher risk numbers for the case when the lidar were stationed on the ISS in comparison to a dedicated satellite is the result of the higher frequency of astronomers intentionally observing the ISS in contrast to a “normal” satellite.

The acceptance of risk for a given space based lidar application depends on the severity assigned to the consequence of an ocular injury and on the choice of the highest tolerable likelihood of this consequence.

5. Conclusions

A probabilistic model for the exposure of different population groups to space based lasers and for the ocular damage once exposure occurs, has been developed and implemented in a generally applicable software. Uncertainty and variability is represented by distributions and are carried through the model by Monte Carlo simulation. Review of the published data for dose-response curves for ocular retinal injury and simulation of the influence of the refractive state of the eye during threshold experiments showed that reported ED-50 and probit slope values should both be reduced when applied to the task oriented eye of an awake human.

The results obtained from the risk model will provide an input to the management of ground population risks induced by the application of space based lidars.

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