A PROBABILISTIC RISK ANALYSIS MODEL FOR RECEIVING LASER EYE INJURY FROM SPACE BASED LASERS

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ABSTRACT

The European Space Agency ESA initiated a study, which dealt with the development of a risk model for laser induced eye injury. This study contributes to the minimisation of risks to the public caused by space flight projects and is summarised in this paper.

The probability of an eye injury occurring in a given potential laser exposure scenario is a combination of the probability of being exposed to the laser beam and the probability of the level of the incident radiation energy producing eye injury. A probabilistic risk model with uncertainties has been developed to quantitatively model the risk for ocular injuries due to laser beams being emitted from satellite based lidars (atmospheric laser measurement systems). The risk model, to the knowledge of the authors, for the first time accounts for uncertainties associated with the variability that an ocular lesion is formed for a given laser exposure, as described by a dose-response curve.

The needs of the user of the model will be summarised, the physical model discussed and the realisation, as generally applicable software, presented.

INTRODUCTION AND USER'S REQUIREMENTS

The use of lidars is considered in a number of ESA's future missions, as well in missions conducted by NASA and NASDA. Spacecraft based lidars are used to measure a range of atmospheric or earth surface properties by analysis of the part of the laser radiation which is directed back to the lidar (lidar can be considered as a laser radar and is an acronym for light detection and ranging). As only part of the laser radiation is scattered or absorbed by the atmosphere, the remaining laser radiation as emitted from the spacecraft is incident on the earth surface, where it might lead to injuries, especially to the eye, if thresholds are exceeded. Exposure of the eye, either naked or through small optical instruments, is usually harmless but exposure of the eye via large telescopes can result in ocular damage.

In order to minimise the risk for ocular injury due to exposure to the laser beam, ESA has initiated a study "Human Risk Analysis Simulator for Space Lidars", carried out by the Austrian Research Centers Seibersdorf with participation of a number of international experts in the field of laser bioeffects and risk analysis (Schulmeister, 2001). The requirements of ESA were to follow a probabilistic approach to determine the occurrence rate for exposure to the laser beam for relevant population groups, to calculate the ocular radiation exposure level with atmospheric scintillation effects included, and then predict the frequency distribution of an ocular injury from a space borne lidar. The model was to be implemented in a flexible and user friendly software to facilitate the risk evaluation of future missions involving lidars. Following ESA's requirements, the probabilistic risk model was developed for the full range of possible orbit and laser beam parameters. Parameters such as orbit inclination, pointing direction of the laser beam, laser wavelength, laser energy, and footprint diameter are specified as input parameters by the user. The uncertainty and variability of model parameters are described by distributions which are propagated through the model with Monte Carlo simulation to produce a distribution of the expected number of ocular injuries per mission (collective risk) and the frequency for ocular injury per hour of using a given type of optical instrument (individual risk).

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 lidar output can also consist of two different wavelengths with different energies, which is included as option in the model. The direction of the line of sight (LOS) of the laser beam is specified as azimuth angle clockwise from the flight direction and by the angle off nadir. The laser energy is decreased by wavelength dependent atmospheric scattering and absorption. This is included in the model by transmittance curves calculated for nadir pointing with atmospheric model software MODTRAN and FASCODE for three atmospheric conditions which form a triangular distribution with "US-Standard" as most likely value. The decrease of transmittance with increasing path-length for off-nadir pointing is accounted for by the cosine law.

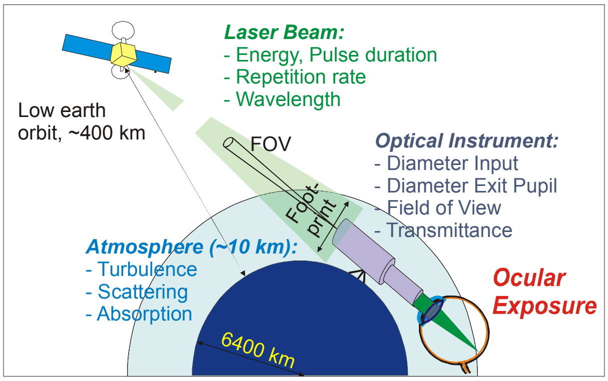


Figure 1. Simplistic schematic depiction of the model scenario.

The beam exposure profile on the earth surface is assumed to be close to a gaussian shape, and the diameter at the points where the local exposure (J/m^2) equals $1/e^2$ is used to characterise the dimension of the footprint. Scintillation effects which cause a variation of the local exposure around the average value are accounted for by the usual log-normal distribution 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 $T(\lambda)$ 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, 2000). The exit pupil diameter typically varies between 1 mm and 7 mm according to the chosen eye piece focal length (which determines magnification and field-of-view), and this is also modelled by a uniform distribution.

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

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.
For satellite (or other spacecraft in orbit) based lidars, P_{ill} is best calculated with reference to a certain range of latitude, i.e. for a ring around the earth with width of e.g. 5 degrees. Resulting from the well defined orbit, P_{ill} for a given latitude is fully determined by the inclination of the orbit, the area of the footprint and the pulse repetition rate. 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. In terms of viewing behaviour with telescopes, three categories are distinguished in the model: general astronomy usage, observation of the International Space Station (ISS) for the case that the lidar is stationed on the ISS, and observation of visible satellites for the case that the lidar is stationed on a satellite other than the ISS. For instance, for general astronomy usage, if it is assumed that telescopes in that category 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°. If the lidar were stationed on the ISS, then P_{FOV} will be 1.0 for somebody who observes the ISS with his telescope.
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 "Ocular Damage Model".
$P_{OD\ ind} = P_{exp} * P_{OD}$

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 model is set up with 5° latitude rings and due to the nature of low earth orbits averaging over longitude as well as time is assumed. 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 $N(\Lambda,G)$ 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. $N(\Lambda,G)$ and F_{time} can conveniently be grouped to one parameter N_{time} (and corresponding distribution) representing the number of optical instruments used at any time.

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.

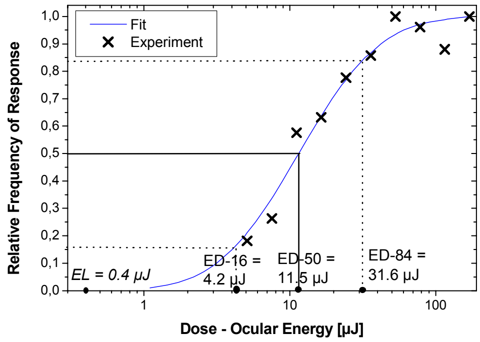
OCULAR DAMAGE MODEL

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. A MVL is defined as a just noticeable lesion, as detected with an ophthalmoscope or by histology. International laser safety exposure limits (EL) are defined by reducing experimental MVL by a safety factor to insure negligible risk if exposure at the EL occurs (ICNIRP 1997, IEC 1993). 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 (Finney 1971). The fit of the data is usually performed according to the "probit" analysis, and the distribution is therefore often called a "probit curve". 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).



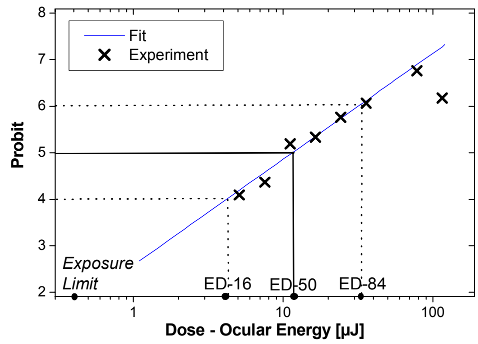


Figure 2. Experimental minimal visible retinal lesion data obtained with short pulsed dye-laser radiation (Lund 2000) is fitted by a cumulative log-normal dose response curve as obtained with probit analysis. Also shown is the laser exposure limit EL for the particular wavelength and pulse duration, which is a factor of 16 below the ED-50.

Previous quantitative probabilistic laser safety studies (Smith 1994) 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 2002). The analysis indicates that thermal and thermoacoustic damage mechanisms apparently have an intrinsic slope of approximately 1.15 to 1.2 (e.g., Bargeron 1989, Sliney 1980), whereas much shallower slopes in the range of 1.3 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.

We argue that dose-response curves for laser injuries should actually not be used for exposure levels far below the ED-50, as for medium to large slope values, a finite probability for ocular damage is predicted. However, from biophysical reasoning, a temperature increase of for instance 1°, as comparable to a mild fever, could not produce a lesion. This could be modelled with a cut-off energy, below which the probability for ocular damage is zero, or with probit curves with steep “theoretical” slopes, which also exhibit a similar behaviour of rapidly decreasing probabilities for energies smaller than the ED-50.
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.

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 (ICNIRP 1997, IEC 1993). 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.

A representative figure for an uncertainty distribution is the "potentiality", which can be defined as the logarithmic mean of the 95 % quantile and the 50 % quantile (RISAN) and which is calculated by the software.
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 for a three year mission.

Wavelength, main ocular absorption site	Potentiality for numbers of ocular injuries for 3 year mission	Main risk contributor
355 nm (lens)	$< 10^{-99}$	Telescopes with 2.5 m diameter no risk contributor
532 nm (retinal pigment epithelium)	$5 \cdot 10^{-4}$	Telescopes with 30-40 cm diameter
1064 nm (choroid)	$1 \cdot 10^{-6}$	Telescopes with 60 cm diameter

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 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.
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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