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Optical Properties of Binoculars and Telescopes Relevant to Laser Safety

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Abstract

For hazard analysis of potential exposure to laser radiation with optical instruments such as binoculars or telescopes, the accuracy of the analysis can be improved when the optical properties of the optical instruments are considered. The paper will present results of measurements and calculations of the transmittance of optical glass, binoculars and telescope eyepieces in the ultraviolet and infrared wavelength region, as well as a discussion of the influence of the diameter of the input optics and the exit pupil on the ocular exposure. Also, for probabilistic risk analysis where the probability that an illumination occurs is considered, the dimension of the field of view of the instrument needs to be accounted for, especially for exposure with telescopes to radiation emitted from space based lasers.

1. Transmittance of Optical Instruments

The ocular exposure for the case that optical instruments such as telescopes or binoculars are used are of concern in laser safety, as optical instruments can collect energy of a beam with large beam diameter which would otherwise not be incident on the naked eye. In IEC 60825-1 the range of 302.5 nm to 4000 nm is specified as the wavelength range were optical instruments need to be considered to be transmitting laser radiation. In ANSI Z136.1, in table 9, the transmission of optical instruments is given for the range of 302 nm – 2800 nm as at least 70 % (90 % in the visible) and as < 2 % outside this wavelength range. Optical glass and plastics which may be used in low-cost instruments, generally absorbs strongly in the UV and in the mid- and far-IR wavelength range, and in these wavelength ranges, optical instruments can be even considered acting as protective filters. Transmittance data in the wavelength ranges with strong absorption do not seem to be available in the literature. Measurement of specially prepared optical glass samples and of binoculars and telescope eyepieces were performed in the wavelength range of 190 nm to 6000 nm.

1.1 Thin Schott Glass Samples

The spectral transmittance of optical grade glasses Schott BK-7 and BaK-4 was measured[1] for glass samples with a thickness[2] of 1 mm and 0.038 mm in order to obtain transmittance data for a wide wavelength range. The two types, BaK-4 and BK-7, were chosen as these types of glass are often used in binoculars and telescopes.

With the assumption of a reflectivity of $R = 0.04$ for each glass-air surface, the spectral absorption coefficient α is obtained with the exponential absorption law of Beer Lambert:

$$T(d) = (1-R)^2 \exp(-\alpha d)$$

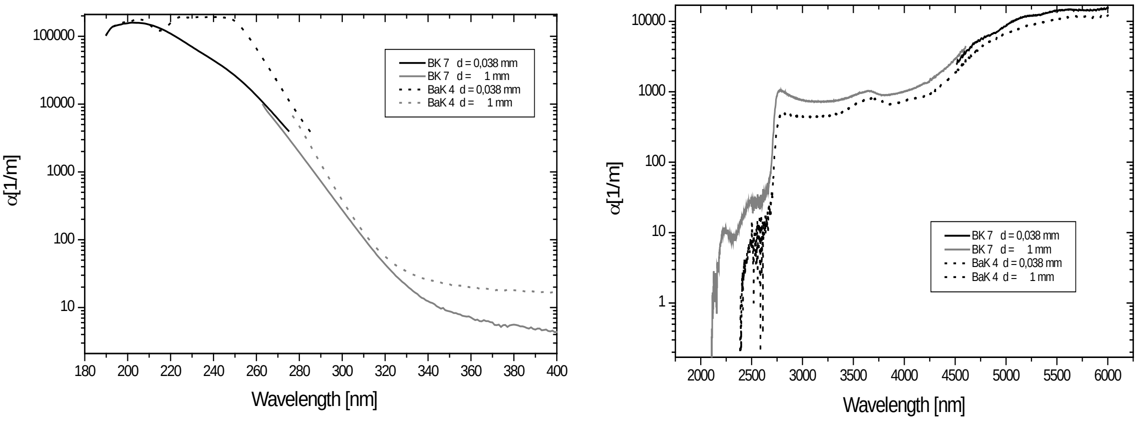

Fig. 1: Absorption coefficient as function of wavelength for the two glass types
BaK-4 and BK-7 in the UV and IR range.

The resulting plots for the absorption coefficient are shown in Fig. 1. The overlapping region of the 1 mm and 0.038 mm samples can be seen. The data of the transmittance measurement of the thick sample are used in the wavelength range where the absorption is small, while the data from the thin sample are used to derive the absorption coefficient for the highly absorbing wavelength range.

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[1] For the wavelength range of UV-VIS-NIR (190 nm – 2500 nm), Spectrometer: Perkin-Elmer Lambda-9
For the wavelength range of IR (2500 nm – 6000 nm), Spectrometer: Perkin-Elmer 682
The uncertainty in UV-VIS is approximately +/- 0.5 %T, for the NIR - IR range approximately +/- 1%T

[2] Measured with Stepper Thickness Measurement System with 1/1000mm resolution. The thickness of the samples varies with about 0.01 mm over the sample size of about 1 cm² due to the grinding and polishing process.

With the data on the absorption coefficient, the transmittance of a glass sample of a given thickness can be calculated.

1.2 Binoculars

The spectral transmittance of three binoculars has been measured in the UV and in the IR range[3]. With a quartz tungsten halogen lamp as source is was not possible to determine the absolute transmittance accurately, therefore the spectral measurements were corrected to fit the transmittance as measured with a Nd:YAG laser (1064 nm) for the IR data and with a 543 nm HeNe laser and an Argon Ion laser in the Visible-UV range.

The Carena binocular is manufactured with polycarbonate lenses, the Swarovski binocular with BaK-4, and the glass type of the Jena binocular is not known. Both the Swarovski and Jena binocular feature coated lenses, which optimize the light transmittance in the visible, but decrease the transmittance in the UV and IR range. This can be easily seen by a comparison with data for uncoated BK-7 glass of a thickness of 6 cm as calculated from the absorption coefficient, as shown in Fig. 2. A thickness of 6 cm was chosen as representative value of total glass thickness in a binocular, which consists of at least 4 lenses and one or two prisms.

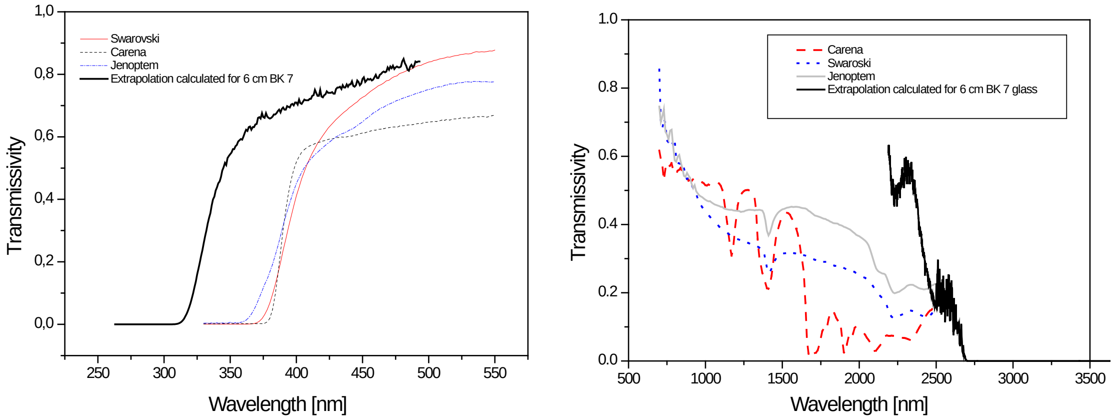

Fig. 2: Transmittance of three binoculars. The data in the IR wavelength range for three types of binoculars in linear scale. In regions without experimental data, transmission has been calculated for 6 cm BK 7 glass.

At a wavelength of 355 nm the transmittance of the binoculars falls below the measurable value. The influence of the antireflection coating can be clearly seen and the use of the Schott data for uncoated glass (in the absence of other measurements) constitutes a worst-case assumption for wavelengths below 355 nm, i.e. the transmittance will certainly be smaller than assumed. In the IR range, the transmittance could be measured up to a wavelength of 2500 nm. For wavelengths above 2500 nm, the Schott data are as calculated for a glass thickness of 6 cm could be adopted as worst case assumption.

1.3 Telescope Eye Pieces

The spectral transmittance of two commercially available telescope eyepieces[4] was measured[5] in the UV spectral range and calibrated with a 543 nm HeNe laser and an Argon Ion laser. The Kellner type eyepiece is representative of simple eyepieces with comparatively simple optics and a correspondingly small mean thickness of glass of 8.5 mm. Due to the small input aperture of the Vixen eyepiece, the correction with laser beam measurements was only possible with a certain uncertainty which is represented by two data sets in Fig. 3; however, the comparison with the data for the Kellner type eyepiece shows the reduction of transmittance for more complicated and thicker optics. It should be noted that both eyepieces are anti-reflection coated.

Measurement in the IR range was not possible due to insufficient instrument sensitivity, and the transmittance calculated from the Schott absorption coefficients with a glass thickness of 8.5 mm is shown in Fig. 3.

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[3] Bentham Double Monochromator Spectroradiometer DM300

[4] Vixen LV 2.5 mm focal length with 8 lenses, 31.7 mm size, and a Kellner type eyepiece KE 10 mm wide angle of unknown make.

[5] Bentham Double Monochromator Spectro-Radiometer DM300

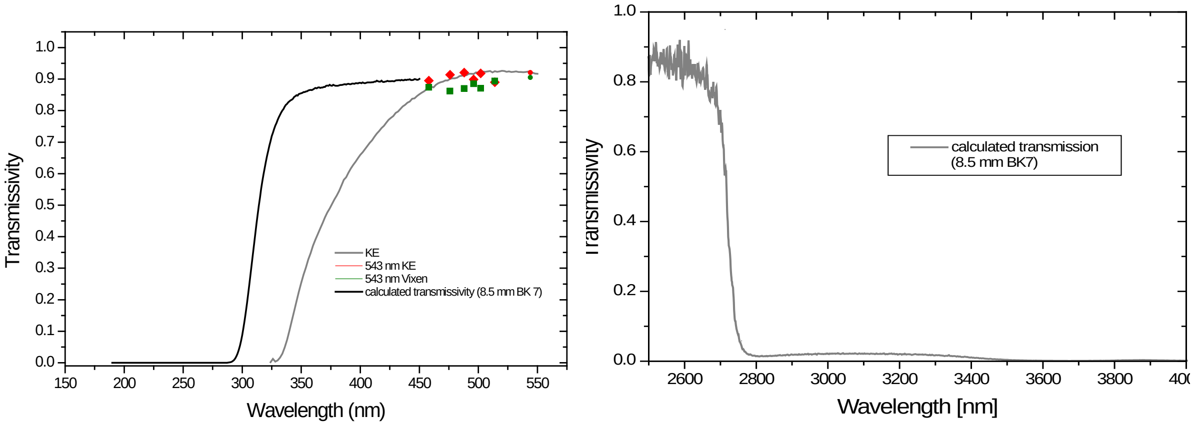

Fig. 3 Spectral transmittance for two commercially available telescope eyepieces and data as calculated from uncoated Schott BK 7 glass for a thickness of 8.5 mm.

2. Geometrical Parameters of Optical Instruments

The geometrical parameters of optical instruments relevant for laser safety are the input optics diameter, the exit pupil diameter (only outside the retinal hazard area), the magnification (increase of apparent source size) and the field of view (FOV, probability for exposure). These parameters as well as their interrelationship will be discussion in the following for telescopes and binoculars.

2.1 Input Aperture Diameter

In respect of an increase of the hazard, the main factor is the size of the input aperture of the optical instrument which is directly related to the light gathering power. For reflectors (e.g. the classic Newtonian telescope), some of the light gathering area of the input aperture will be lost due the second mirror, hence the effective input aperture diameter will be smaller.

The maximum input diameter of binoculars which are sold in larger quantities is 50 mm. Some special groups as the military, birders and satellite observers may use binoculars and spotting scopes with 8 cm input diameter, however these are very expensive. Even larger binoculars exist on the market (10 cm Miyauchi and Vixen, 15 cm Fujinon), however these are extremely expensive, and also large and heavy.

2.2 Focal Length

The focal length of the telescope f (i.e. the distance of the focus of the parallel incoming beam of light from the focussing element) is given by the choice of primary mirror for a reflector or by the choice of objective lens for a refractor. Together with the focal length of the eyepiece f_{EP} determines the magnification $M = f / f_{EP}$. The f-ratio, f/, of a telescope is defined as the relation of focal length of the telescope to the diameter of the input aperture, $f/ = f / D_{in}$, i.e. relates the light gathering power (D_{in}) with the possible magnification (f). The usual way of denoting the f-ratio is for instance f/4 or f/12, meaning the focal length is 4 and 20 times the input diameter, respectively.

2.3 Exit Pupil Diameter

The exit pupil is an imaginary part of the beam exiting the eye piece. It is defined as the section of the emergent light pencil, through which rays from every point in the visible field pass. The diameter of the exit pupil, D_{exit}, is relevant for the determination of the hazard for wavelengths outside the retinal hazard region of 400 nm to 1400 nm (as for the retinal hazard region, the averaging aperture is 7 mm), as it is the position where the exiting light beam has the smallest diameter and therefore the highest irradiance behind the eyepiece. The size of the exit pupil diameter follows the following relationships:

$D_{exit} = f_{EP} / \text{f/ratio}$ or $D_{exit} = D_{in} / M$

For commercially available eyepiece focal lengths in the range of 2.5 mm to 40 mm and with f-ratios of telescopes in the range of f/4 to f/20, the exit pupil can be in the range of 0.25 mm to over 10 mm. However, an exit pupil diameter of less than 1 mm results in a magnification which is too large to practical and an exit pupil larger than 7 mm is not practical because the maximum diameter of the pupil of the human eye is 7 mm (i.e. if the exit pupil is larger than 7 mm, brightness is lost). In extreme cases, a 40 mm focal length eye piece (with an exit pupil of 10 mm) can be chosen to obtain a very large field of view.

For binoculars, the minimum exit pupil of commercially available binoculars identified in this study is 2.5 mm for the Pentax PCF III 20 x 50; however, such large magnifications are rather rare. A typical minimum exit pupil diameter for “general application” binoculars is 3.5 mm, for example, for the Swarovski SLC 8 x 30.

2.4 Field of view

The field of view (FOV) specifies the angle which can be seen through the optical instrument. The size of the FOV is relevant for risk analysis, since the source of the beam has to be in the FOV in order that ocular exposure can occur, and for cases other than direct intentional observation of the source, a small FOV results in a correspondingly small probability for ocular exposure. The apparent FOV is given by the optical design of a particular eye piece, and is the angle which is seen when looking through the optical instrument. For instance a RKE eye piece has an apparent field of view of 45°, while a Nagler has an apparent field of view of 82°. The real FOV is the angle (as part of the firmament) which is actually seen. The real FOV is related to the apparent FOV by $real\ FOV = apparent\ FOV\ / M = apparent\ FOV / (f/f_{EP})$

The FOV of telescopes is usually specified as plane angle in degrees. Generally the simpler eyepieces (small number of lenses) have a much smaller field of view than expensive ones. The real field of view for a given telescope with a certain focal length is determined by the focal length of the eyepiece, which in turn determines the magnification. Therefore, for a given telescope, a smaller magnification (larger focal length of the eyepiece) results in a larger field of view. The usual equipment of an amateur astronomer will be a high-magnification eye piece with a small of view of around 0.2° – 0.3° and a “wide angle” eyepiece with lower magnification and a field of view of about 1.5° – 2°. In the following section, minimum and maximum values for the field of telescopes are derived.

2.5 Relationships

Generally, the FOV is smaller for larger telescopes: the f-ratio of commercially available telescopes ranges from f/4 to about f/12. Due to the minimum value of the f-ratio of f/4, a larger input diameter of the telescope results in a larger minimal focal length. In turn, a larger minimal focal length results in a range of possible magnifications which is shifted to higher values (with an exit pupil diameter between 1 mm and 7mm), which itself results in a range of FOV values which are shifted to smaller values. Typical values are shown in .

Tab. 1. Dependence of the range of the FOV on the size of the telescope

Input Diameter	min. focal length	min M (D_{in} / 7 mm)	max FOV*	max M (D_{in} / 1 mm)	min FOV**
10 cm	400 mm	14	4.5°	100	0.90°
30 cm	1200 mm	43	1.5°	300	0.30°
50 cm	2000 mm	71	0.9°	500	0.18°
100 cm	4000 mm	143	0.45°	1000	0.090°

* Pentax XL eyepiece with 4 mm focal length **Pentax XL eyepiece with 28 mm focal length

The Pentax XL eyepiece has been chosen as a high quality eye piece with a large apparent field of view of 65°. It should be noted that telescopes with f-ratios up to about f/12 are available. A larger F-ratios and therefore larger focal length results in a smaller FOV for the same eyepiece than given in the table above.

The field of view of binoculars and spotter scopes is often given in meters at 1000 m distance or as feet at 1000 yards. Typical values for real FOV are 2°-3°, for high quality binoculars the field of view can be as large as 7° - 8°.

Conclusions

The transmission of specially prepared optical glass samples, as well as commercially available binoculars and telescope eye-pieces was measured from UV to IR wavelength ranges. Approximate transmission data specified in ANSI Z136. compares well with measured and calculated transmittance data.

For probabilistic risk analysis, the field of view is related to the probability for inadvertent exposure. The minimum and maximum FOV is related to the input diameter of telescopes: the larger the telescope, the smaller the FOV and the smaller the probability for exposure.

For calculation of the ocular exposure level, the exit pupil diameter needs to be considered for wavelengths outside the retinal hazard region.

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