

Holger Merlitz

The Binocular Handbook

Function, Performance and Evaluation
of Binoculars

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Foreword

*Wisdom resteth in the heart of him that hath understanding.
Proverbs 14:33*

It was while conducting research for my own book, *Choosing & Using Binoculars: A Guide for Stargazers, Birders and Outdoor Enthusiasts* (Springer Nature 2023), that I first came across the work of Holger Merlitz. I was attempting to flesh out the factors which affect depth of focus in binoculars, when I hit on a 2002 Cloudy Nights post by Holger, which provided just enough information for me to ‘reverse engineer’—albeit with a little algebraic manipulation—the main factor (magnification) involved. I’ve since learned that Dr Merlitz, a senior researcher of theoretical physics at the Leibniz-Institute of Polymer Research Dresden, Germany, is a towering figure in the world of binocular optics, having published a string of influential papers—both for the amateur and professional optics community—over many years that have received international approbation. Indeed, the optics giant, Zeiss, recently adopted Dr Merlitz’s theory with an eye to designing their new SFL binoculars, employing his ‘ideal distortion profiles’ to create a uniquely comfortable panning experience.

The Binocular Handbook: Function, Performance and Evaluation of Binoculars, freshly translated into the English language, is the culmination of decades of work carried out by Holger, often in his spare time. In just nine chapters, Dr Merlitz walks the reader through the fascinating world of binoculars, their nuts and bolts, the optical principles underpinning their design, as well as the role of the human eye in engaging with the binocular image. In this volume, you’ll find the answers to all sorts of interesting questions. Can a binocular generate a brighter image than that seen with the naked eye? What factors govern depth perception? Does a binocular need to have a flat transmission profile across the visible spectrum to produce images rich in natural colours? How do phase correction coatings really work? Are roof prism binoculars better than Porro prism designs? Is argon really a better gas than nitrogen in rendering a binocular fog proof?

The book is divided into three neat sections. Part I covers the basic optical principles including aberrations, glass and prism types and the principles of eyepiece design. Part II delves into the fascinating subject of human vision and how it responds in bright and dim light conditions, depth and colour perception, stereopsis

and some interesting laws that govern these parameters. Finally, in Part III, Dr Merlitz discusses the interface between the human eye and the binocular, discussing concepts such as luminance, contrast and resolution as they apply to imaging through a binocular and how the interplay between these factors changes as the ambient light changes. In addition, Merlitz offers some of the best advice I've seen for field testing binoculars, doubtless informed by his own extensive hands-on experience with a plethora of contemporary and classic binocular models.

One of the great strengths of this volume is that it's grounded on well-established physical principles, which sets it apart from unbridled speculation too often experienced in online forum discussions. The unwary novice can spend months or even years going round and round trying to comprehend an optical concept without ever gaining much in the way of understanding. This work offers a powerful panacea for such wanderings in the desert. The diligent reader will be rewarded with expert analysis, but not in a way that quickly loses the attention of the student. Holger has a real gift at making difficult concepts much easier to understand using vivid analogies from the workaday world. These skills will greatly endear the work to a wide readership, including birders, hunters, amateur astronomers or indeed anyone who wants to understand and better enjoy what he/she is seeing through their binoculars. It will also help the prospective buyer to sift through the morass of advertising hype, thereby empowering the reader to make informed decisions on purchasing an instrument before parting with their hard-earned cash. Without a shadow of a doubt, this tour de force in binocular optics is not likely to go out of date any time soon—surely a hallmark of a classic work in optical science.

Fintry, Scotland, UK
June 20 2023

Dr Neil English

Preface

Binoculars are fascinating instruments: once placed in front of the eyes, they allow the user to immerse himself in an altered reality. First of all, distant objects appear to be closer. But binoculars do much more than a simple magnification: the image of a good binocular is so vivid that it seems to invite the viewer to participate in what is being observed. On the contrary, a conventional telescope excludes from what is seen in its image—the observer always seems to remain an external element.

Hidden behind the magic of binocular observation is the human visual perception, which unfolds its full capacity only in the context of two-eyed vision. It would therefore be misleading to judge a binocular solely by its optical and mechanical components, since its performance in practical use emerges in close cooperation with visual perception: the eye and the fieldglass, man and machine, form a symbiosis, whose characteristic properties arise from the mutual interaction between the image forming and the image processing layer.

This book attempts to treat binoculars in such a broader context. In the first two parts, the technical aspects of binoculars and the properties of human visual perception are developed. Subsequently, the synthesis is carried out and the performance limits, as experienced by the observer in a variety of external conditions, are derived. Finally, this book takes the reader outdoors, where he learns to evaluate the properties and limitations of his binoculars in the field, and to recognise possible problems that may be due to manufacturing errors or accidental damages. Thus, a level of knowledge is provided that will enable the reader to fully exploit the capacities of his binoculars and to avoid bad purchases.

Dresden, Germany
June 2023

Holger Merlitz

Acknowledgements

This book has not been written in isolation. Large parts of the content are the result of countless discussions between the author and other binocular enthusiasts and experts. In particular, the Internet with its discussion boards has made communication between people of different backgrounds possible. The author is grateful to the participants and operators of the forums on www.juelich-bonn.com, forum.astronomie.de, www.cloudynights.com and www.birdforum.net.

It would be impossible to name everybody who, with his ideas and suggestions, has contributed to the knowledge that is condensed in the present book. I want to explicitly thank Walter Besenmatter, Dominique Blach, Börries von Breitenbuch, Bill Cook, Jan van Daalen, Gerhard Eller, Stefan Emsel, Beat Fankhauser, Dale Forbes, Gijs van Ginkel, Stephen Green, Albrecht Köhler, Stefan Korth, Tobias Mennle, Mathias Metz, Klaus Müscher, David W.J. Norton, Arek Olech, Andreas Perger, John Russel, Walter Schwab, Hans Seeger, Barry Simon, Volker Tautz, Hans Weigum, Heiko Wilkens, Wolfgang Wimmer and Ed Zarenski, and apologise to those which I have forgotten to mention.

I am particularly grateful to Christophe Zumstein, who helped with the translation and continuously encouraged me to forge ahead with the making of this edition, as well as to Dr Neil English, who wrote the foreword for this book and more than once offered his kind support whenever I needed assistance. Last but not least, I want to thank the editorial team of Springer Nature for their professional and patient efforts to make this book possible.

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Part I
The Technical Aspects of Binoculars

Chapter 1

Optical Imaging



1.1 Light in a Vacuum

Visible light is the term used to describe electromagnetic radiation in the wavelength range between about 400 nm and 700 nm. This **visible range** is actually only a very small part of a much broader electromagnetic spectrum, which extends into the short-wave regime, through the UV (ultraviolet) into the X-ray range, up to gamma radiation and into the long-wave regime via the IR (infrared) and microwaves up to radio waves. The classical theory of electromagnetic radiation was developed by Maxwell in 1864 in the form of the famous equations named after him, and its modern incarnation, quantum electrodynamics, dates from the late 1940s.

According to both approaches, light in a vacuum exhibits no **dispersion**, i.e. the **wavelength** λ is related to the **frequency** ν via a constant factor c ,

$$\lambda \cdot \nu = c, \quad (1.1)$$

known as the **speed of light** in vacuum, $c = 2.99792458 \times 10^8 \text{ m s}^{-1}$.

The visible spectrum encompasses the colour range between the short-wave violet to long-wave red. For the definition of selected wavelengths, one traditionally uses the **Fraunhofer-lines**, which the optician Fraunhofer¹ observed in the spectral decomposition of sunlight for the first time around 1814, but which had been described before by Wollaston² in 1802 (Fig. 1.1). These **absorption lines** are caused by various chemical elements, which exist in traces in the atmospheres of the sun and earth. If light passes through these atmospheres on its way into the observer's spectrometer, these elements are excited at very specific frequencies at which the intensity of light appears weakened. The excited ions re-emit light of the same wavelengths, but in random directions, resulting in an observed dimming in the

¹ Joseph von Fraunhofer, 1787–1826.

² William Hyde Wollaston, 1766–1828.

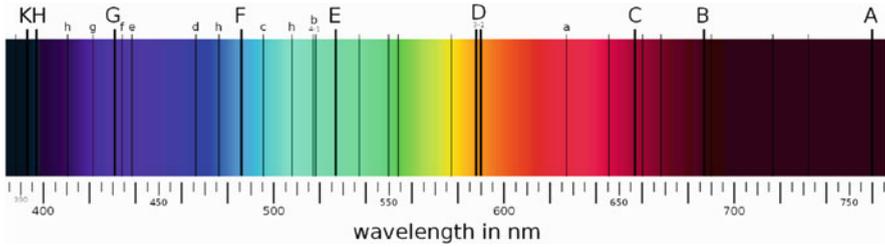


Fig. 1.1 Spectral decomposition of visible light with Fraunhofer lines

direction of the light source, i.e. the sun. Since these lines are easily generated in the laboratory, they are ideal for measurement purposes and for the calibration of instruments. The most common absorption lines are named with letters, for example the G-line of iron (430.790 nm), the D double line of sodium (588.997 nm and 589.594 nm) or the C-line of hydrogen (656.281 nm).

1.2 The Law of Refraction

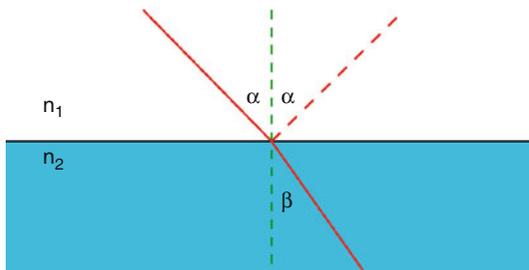
Geometrical optics is a field that deals with the behaviour of light in different media. It is called geometric, because it is based on the assumption that the propagation of light can be described as a ray, whose trajectory obeys certain geometric laws. This is remarkable, because light is a rather complex electromagnetic oscillation phenomenon, obeying Maxwell's field equations. Geometrical optics nevertheless works amazingly well, which has to do with the fact that the wavelengths of visible light are usually much smaller than the optical components we have to deal with in everyday life.

The core of geometrical optics is the law of refraction, which became popular in Europe through the work of the Dutchman Willebrord van Roijen Snell in the early seventeenth century, after whom it is nowadays named as **Snell's law of refraction**.³ It provides the relationship between the angle of incidence and the exit angle of a light ray at the interface of two transparent media with different **refractive indices** n_1 and n_2 . Referring to Fig. 1.2 one obtains

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1}, \quad (1.2)$$

³ Apparently, the law was already known during the tenth century in the Persian area, as it appears on a handwritten text by Abu Sad al-Ala ibn Sahl (about 940–1000). See also the discussion in the book by Iqbal [1].

Fig. 1.2 A beam of light (red) at the interface between two transparent media of different optical densities. Refraction occurs (solid line) as well as reflection (dashed line)



where the angles are taken to the perpendicular (or normal to the surface) of the interface. The [refractive index](#) of a vacuum is exactly $n = 1$, and that of air under normal conditions amounts to $n = 1.0003$, practically the vacuum value. Since optical glasses have far higher refractive indices than that, we will be able to set the refractive index of air to $n = 1$ without sacrificing the accuracy of the results.

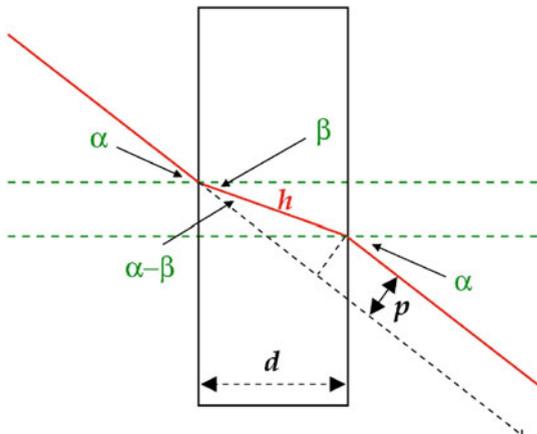
For reflection, the simple [law of reflection](#) applies: angle of incidence = angle of exit. That is about all is required—starting from the law of refraction and the law of reflection, we are in a position to derive the course of rays through most complicated optical systems by calculating the angular ratios of incoming and outgoing rays at each point of incidence on the respective interfaces. This procedure is called [ray-tracing](#) and was largely carried out manually until the 1940s. At that time, the optical calculating bureaus employed human ‘computers’ whose tedious task was to track ray bundles with pencil and ruler through optical arrays, supported by mechanical calculating devices. Only after the Second World War were program-controlled computers increasingly employed for ray-tracing tasks. In Germany, Ernst Leitz AG in 1953 put a Zuse Z5 machine into operation for the purpose of computer-aided lens design, followed by the East German Carl Zeiss Jena company (1955, an in-house computer design by Wilhelm Kämmerer, named OPREMA) and Zeiss (West) in Oberkochen (1956, Zuse Z11) [2].

For illustration, we calculate the path of a light beam through a planar [glass plate](#)—a simple case of ray-tracing, which already reveals some of the typical properties of an optical element (Fig. 1.3). The glass plate has the refractive index n and a thickness d , and the light beam (red line) an incident angle α to the perpendicular (green line). The angle of refraction inside the optically denser glass then results from the law of refraction to

$$\beta = \arcsin\left(\frac{\sin \alpha}{n}\right). \quad (1.3)$$

Inside the glass plate, the light beam covers a distance of $h = d/\cos \beta$. When the beam leaves the glass plate, it passes from the optically dense medium into the optically thinner air, and the exit angle is identical (α) to the one at which it had previously hit the plate. Beyond the glass plate, light rays thus propagate in the same direction as before, but they are offset by a certain amount. This [parallel displacement](#) p can be easily computed from the triangle enclosing the difference

Fig. 1.3 A glass plate of thickness d is traversed by a light beam. The angle of incidence to the perpendicular (green) is α , the parallel offset of the outgoing beam is p



angle $\alpha - \beta$, whose hypotenuse h is the light path in the glass ($d/\cos\beta$) since $\sin(\alpha - \beta) = p/h$. It then follows that

$$p = h \sin(\alpha - \beta) = d \frac{\sin(\alpha - \beta)}{\cos\beta} . \quad (1.4)$$

So let the thickness of the glass plate be 5 cm, the angle of incidence 30° and the refractive index $n = 1.57$, corresponding to a BaK4 glass which is commonly used in image erecting prisms. With these input data, we then obtain an angle $\beta = 18,57^\circ$ and thus the parallel offset to $p \approx 1.05$ cm.

It has been common in technical optics to use approximations in order to simplify the resulting formulas. Trigonometrical functions can be expanded into power series, such as for sine

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots , \quad (1.5)$$

or for cosine

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \dots , \quad (1.6)$$

where the angle must be entered in radians, i.e. the angle (in degrees) multiplied by π and divided by 180. In fact, each pocket calculator computes its built-in trigonometrical functions with the help of these series expansions, which in principle have an infinite number of terms, but which in practice are truncated after a couple of terms, once a sufficient degree of accuracy has been reached. During the times in which these calculators were not yet available, Gauss⁴ developed a

⁴ Carl Friedrich Gauss, 1777–1855.

computation scheme for his optical calculations which employed only the leading order (linear) terms of the expansions, e.g. $\sin x \approx x$ and $\cos x \approx 1$. This framework, which is accurate only for small angles, is known as **Gaussian optics**.

In the Gaussian optics approximation, the law of refraction simplifies to $\beta = \alpha/n$, and the parallel offset to

$$p \approx d \alpha \left(1 - \frac{1}{n} \right), \quad (1.7)$$

which for our example ($d = 5$ cm, $\alpha = 30^\circ$ and $n = 1.57$) yields 0.95 cm, quite far from the more accurate result of 1.05 cm, since the angle of incidence was not exactly small. Let us repeat the calculation with an angle of incidence of 4° , then we obtain the parallel offset to 0.1269 cm (exact calculation) and to 0.1267 cm (Gaussian approximation), which are almost identical.

If Eq. (1.4) is expanded up to terms that include third powers of the angle α , the computation scheme results in what is known as **Seidel's error theory**. The Seidel approximation allows an in-depth analysis of some of the higher-order aberrations, which are excluded from the simplified equations of the Gaussian theory. Obviously, in modern, computer-driven optical design these different levels of approximation have become obsolete—equations are number-crunched to any level of accuracy within fractions of seconds. Yet, traditional approximations are still applied in order to classify the primary sources of imaging errors and thus support the evaluation of the properties of a new optical design.

1.3 Refractive Index and Dispersion

The above-mentioned refractive index n is a material property of glass. Light is an electromagnetic wave that stimulates the countless atoms of the glass to oscillate—to be more precise, it is the atomic shells, formed by electron clouds, which oscillate in the electromagnetic field. During this process, the electrons are not excited, i.e. not lifted to higher energy levels, since if that happened, the light would be absorbed and the glass would no longer remain transparent. Now the electron shells have their own preferred oscillation frequencies, called **natural frequencies**. Since the frequency range of the incident light does not coincide with this natural frequency, the atoms cannot oscillate exactly in phase with the electromagnetic wave, and through their own oscillations, they themselves generate a secondary electromagnetic field that is superimposed on that of the incident light. Thus, a new effective field is generated, which is associated with an altered, frequency-dependent **phase velocity**. This is the reason why light, when passing through a transparent medium, alters its phase velocity, which leads to the observed refractive index and to deflections, as described by Snell's law.

From what has been said, it is understandable why the exact value of the refractive index depends not only on the material, but also on the light: The phase shifts depend on the ratio between the natural frequency and on the (vacuum-)

frequency of the incident light. The dependence of the refractive index on the wavelength is called **dispersion**. In most cases, the refractive index increases with the frequency, but exceptions occur near the natural frequency: close to the resonance, the refractive index drops with increasing frequency, a phenomenon called **abnormal dispersion**, which is of great practical importance for the correction of chromatic aberrations in optical systems.

How exactly then does the refractive index depend on the wavelength λ of the light? This relationship is specific to each type of glass, but it is so complex in detail that there exists no general law derived from first principles (in other words: it is not yet fully understood). For this reason, technical optics relies on series expansions of the form

$$n^2(\lambda) = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8}. \quad (1.8)$$

When this formula is fitted to the measured dispersion curve of a particular glass sample, the empirical coefficients $A_0 \dots A_5$ are determined and subsequently listed in the glass catalogues of the manufacturers.

1.4 Optical Glasses

So if the refractive index depends on the wavelength, how can it be given for each individual type of glass? For this purpose, it has been agreed that the yellow d-line of ($\lambda_d = 587.6$ nm) wavelength would serve as the basis of the so-called **d-system**. The refractive index n_d at this wavelength is defined as the **principal refractive index**.⁵ The **principal dispersion** is the difference between the refractive indices in the blue and in the red spectral range, more specifically between the F-line (n_F , $\lambda_F = 486.1$ nm) and the C-line (n_C , $\lambda_C = 656.3$ nm). Finally Abbe⁶ introduced the quotient

$$v = \frac{n_d - 1}{n_F - n_C}, \quad (1.9)$$

known as the **Abbe number**. Glasses with low dispersion (**ED-glasses**) then exhibit a high Abbe number. In the glass catalogues of the manufacturers, the different glass types are listed in two-dimensional diagrams, the axes of which being the Abbe number and the principal dispersion (Fig. 1.4).

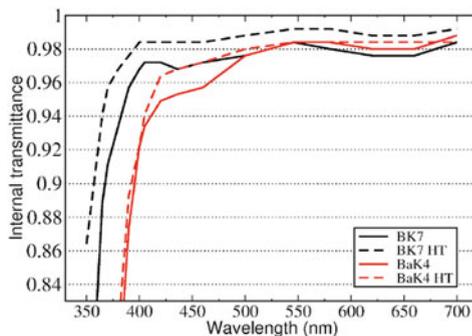
⁵ There exists a second convention, which is based on the e-line of mercury ($\lambda_e = 546.1$ nm) and consequently called the e-system.

⁶ Ernst Karl Abbe, 1840–1905.

Table 1.1
 Visual-transmittance classes of optical glasses: guaranteed internal transmittance τ_{vi} , averaged over the spectrum of visible light through a distance of 100 mm of glass path

Quality class	τ_{vi}
9	≤ 0.859
8	0.860
7	0.880
6	0.900
5	0.920
4	0.940
3	0.960
2	0.980

Fig. 1.5 Internal transmittance: conventional BK7 and BaK4 glasses and the new HT-variants, converted to 10 cm glass path (visible light: 400–700 nm; data courtesy of SCHOTT AG, Advanced Optics)



is considered high quality and glasses of transmission class 2 have to be picked from carefully selected glass melts, are expensive and not always available. High-transmission classes are of particular relevance for binoculars, as these incorporate image erecting prisms with typical glass path lengths of 10 cm or more.

Progress is still being made in this field today, as the recently introduced **HT-glasses** (HT for ‘high transmission’) from Schott suggest. Figure 1.5 shows a comparison of the internal transmittance of conventional BK7 and BaK4 glasses with their corresponding HT variants. The results are shown for the highest visual transmittance class that is available as standard, usually class 3 for the majority of conventional glass types. Within the interval 400 nm to 700 nm, there is an average advantage for BK7 HT over conventional BK7 of at least 1.2 % following a glass path of 10 cm. BaK4, which is a glass of high refractive index and used in most image erecting prisms, is somewhat less transparent in the blue spectral range—the new HT version achieves some improvements here, between 400–500 nm, but offers no further advantages within the rest of the visible spectrum. At least the somewhat flattened transmittance curve should provide an improved **colour neutrality** than its conventional BaK4 counterpart, which is known for its slightly warm (yellowish) colour tint. Whether the investment in expensive HT glasses is worthwhile has to be decided for each individual optical design.

In the binocular industry, the use of **special optical glasses**, in particular for military optics, was not uncommon. These included glass types which achieved a high refractive index through the addition of lead, to be used for the image erecting

prisms of wide-angle optics (Sect. 3.1.1), or exhibited an improved resistance to radioactivity through the addition of cerium oxides. Most of the rather toxic special glasses that were used in earlier times have since been replaced by environmentally friendly glasses. Of particular relevance for the optical design of camera lenses, telescopes and binoculars has been the gradual replacement of **fluorite crystals** (CaF_2), which are difficult to coat and to work mechanically (because they are brittle), by special glasses which include **fluoride ions** (commonly known as ‘ED glasses’, Sect. 4.1) with similar abnormal dispersion characteristics but superior mechanical properties.

Unfortunately, modern-day marketing adds to the confusion among the technical terms. For example, some manufacturers advertise the use of ‘HD-glass’, where ‘HD’ stands for ‘high definition’. Such types of glass do not exist in the databases of any glassworks—a high image definition is the result of a good optical design in combination with precise manufacturing.

1.5 Ray-Tracing a Lens

Section 1.2 has described the ray-tracing through a planar glass plate, by which the light beam has been found to be offset but unchanged in its direction. In order to build optical systems that can focus light, we will need an optical element featuring a curved surface—a lens. We shall now apply our trigonometrical methods to compute the path of rays through a lens with one planar and one spherical surface.

We construct the lens as shown in Fig. 1.6 by taking a sphere of glass with radius R and cutting off a cap of thickness d . Even though the figure shows a complete sphere for illustration, we assume that only the spherical cap on the left side is made of optical glass. We have thus made a **plano-convex lens**, one surface of which being planar, and the other, spherically curved outwards. Almost all lenses used in binocular design have spherical surfaces, because they can be ground easily and with high precision. Other, **aspherical** lens shapes are possible, but are rather difficult to shape and expensive (if made of glass) or of limited quality (if moulded from plastic). As the **principal axis** or **optical axis** we denote the straight line passing from left to right through the lens vertex and the centre of the sphere. Light rays that enter the lens along the principal axis are passing straight through without being deflected.

We now assume that all light rays entering on the left are parallel to each other and to the principal axis, as would be the case with binoculars that focus on a distant point-like object (such as a star) in the centre of the image. A bundle of rays with these properties is referred to as the **principal beam**. The subset of rays which run very close along the principal axis (for which the Gaussian approximation is valid) are called **paraxial rays**.

As an example, Fig. 1.6 shows a single ray (red) that hits the lens from the left at a height h above the principal axis. At this point it is deflected according to the law of refraction, passes through the lens along a straight path and exits the lens at the