OE Optical Engineering

RESEARCH PAPER

Dealing with telescope magnification and resolution: recreating Galileo's observations in the lab

Antonio Marzoa[a,b,*] **and Santiago Vallmitjana**[c]
[a]Universitat Politècnica de Catalunya, Departament de Física, Castelldefels, Spain
[b]SENER Aeroespacial, S.A., Parc de l'Alba, Cerdanyola del Vallès, Spain
[c]Universitat de Barcelona, Departament de Física Aplicada, Facultat de Física, Barcelona, Spain

ABSTRACT. We present practical laboratory work for master's students in photonics. The laboratory session is based on the construction of a telescope, emulating the one used by Galileo Galilei and analyzing the effect of aberrations and other practical limitations on the quality of the image. Different situations and configurations are analyzed, and the recreation of historical observations is carried out to generate a debate on the limitations of real telescopes with the students. The impact on the learning procedure of the students is analyzed by means of the results they have obtained during several academic years.

 [DOI: 10.1117/1.OE.63.7.071412]

Keywords: optics; telescope; image quality; optical design; resolution

Paper 20240072SS received Jan. 20, 2024; revised Apr. 16, 2024; accepted May 3, 2024; published May 21, 2024.

1 Introduction

Geometrical optics is a key issue for optical and photonics engineers and physicists with specialization in optics and photonics.[1,2] Moreover, in undergraduate studies, geometrical optics is typically taught briefly and just from the theoretical and problem-solving point of view, and students rarely experience the procedure of building an optical instrument nor analyze and quantify the role of aberrations or other limitations in real systems.[3,4] Furthermore, resolution is another issue that is analyzed from simply a theoretical standpoint, and students barely deal with the task of obtaining a quantitative interpretation. All these difficulties introduce problems and limitations that future optical engineers may have to deal with in their professional careers.

In addition, it is interesting to point out that optical instruments are not only being currently used in a broad spectrum of applications, both in industry and academia, but also have played a pivotal role in the history of the development of mankind,[5] especially in the fields of astronomy[6] and biology.[7,8] Many of the advances in these areas have been possible thanks to improvements in the quality and magnification capabilities of their instruments, allowing researchers to see more distant systems and smaller objects. However, it is not only the magnification but also the resolution that indicates the performance because diffraction (i.e., the wavelength) defines the theoretical limit for which a particular imaging system is capable of separating two close objects. In addition, aberrations deteriorate the resulting image, limiting the information available to the scientists.

*Address all correspondence to Antonio Marzoa, antonio.marzoa@upc.edu

For these reasons, in the master of photonics[9] taught in Barcelona (a master's degree with students from a myriad of backgrounds, ranging from BSc in physics to BSc in optometry, and different engineering degrees), an experimental laboratory work to offer students a hands-on experiment in geometrical optics, construction of optical instruments, resolution and aberrations was designed and offered as part of the syllabus of the compulsory course photonics laboratory from academic year 2013–2014 to 2018–2019.[10]

This practical exercise to introduce advanced students (master's degree students) to aberrations, resolution, and optical design, among other disciplines related to real optical instruments, is presented in this article. Moreover, the work comprises a motivational historical background: the recreation of Galileo's early observations of Saturn's rings, for the purpose of showing an interesting and historically relevant situation where the resolution and performance of optical instruments at a particular moment in time played a key role in scientific discovery. Thus, this work describes both an experimental practice useful for master's students, as well as a historically interesting recreation.

This work is presented so that it can be used by both students and professors as a guide to implement and develop the practical experience presented. First, a historical introduction and motivation for the work are presented, followed by a presentation of the theoretical background required to develop the experiment.

Subsequently, the practical experience is explained and put into the context of the Barcelona MSc degree in photonics, and the results are presented (in this work, we present a collection of results from students of said MSc). Finally, the interests and advantages of this experience are discussed.

1.1 Historical Background and Motivation

In August 1609, the Italian physicist and mathematician, Galileo Galilei (1564–1642) presented his telescope and started working on different variations of his design which allowed him to magnify distant objects 20 to 30 times.[11,12] He pointed his instrument to the night sky and started a revolution in astronomy.[12–14]

In 1610, Galileo reported observations on the planet Saturn with his telescope and assumed that such a planet was a "triple" system, since he observed two bulges, "ears" or "anses" (or "handles") around the main body.[15] Nowadays, we know that the structure that he observed was the ring of the planet, but at the time, Galileo was incapable of resolving (i.e., distinguishing) the rings, and the planet appeared to have a "peculiar" shape (see Fig. 1), which made him consider that two "small stars" or moons were companions of the planet.[16,17]

Two years after these observations, in 1612, he reported that he observed that the planet was "perfectly" round, without the bulge-type companions.

Finally, in 1616, he observed again Saturn's "ears" in a different position, that he drew (see Fig. 1).

It was not until March 1655, when the young Dutch astronomer, Christiaan Huygens (1629–1695), used his telescope, which presented better optical quality than Galileo's and was able to magnify the image of distant objects up to 50 times, that the mystery of Saturn's "ears" was solved: the planet presented rings that encircle its equator (see Fig. 1), and depending on the relative position of the rings plane and the Earth, the rings were clearer (see Fig. 2).[17,18] The interested reader is referred to Ref. 15 for a more detailed description of the history of this discovery.

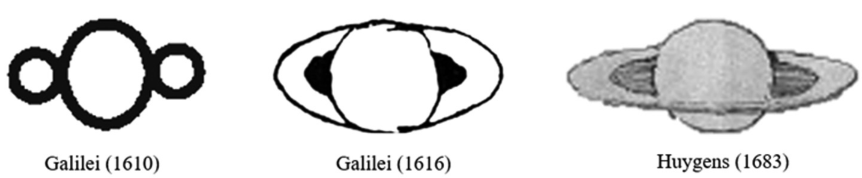


Fig. 1 Sketches from Galileo's early (1610 and 1616) and Huygen's later (1683) Saturn's rings observations.

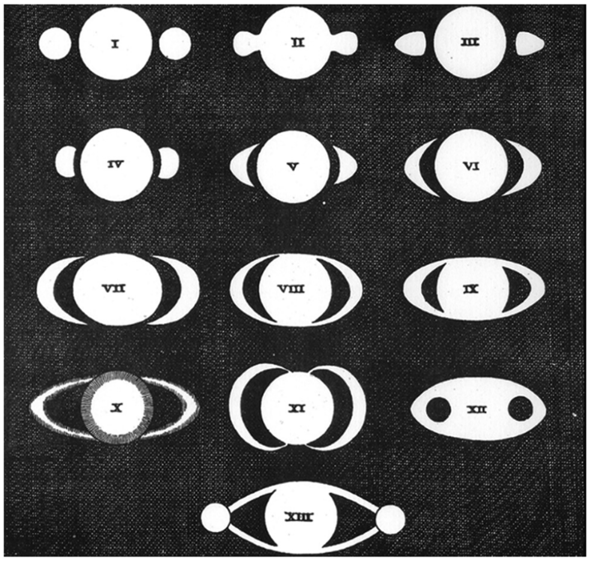


Fig. 2 Compilation of drawings of Saturn from Christiaan Huygens showing the changes in Saturn's rings' appearance between 1610 and 1646. The image corresponds to a sketch of Huygens' work *Systema Saturnium* (1659).

2 Theoretical Background

This section briefly describes the main principles of refracting telescopes and presents an introduction to optical aberrations and the importance of spatial resolution. For a deeper understanding and more detailed introduction, the interested reader is referred to Refs. 1–3 and 19.

Telescopes are optical instruments specifically designed for the observation of distant objects. For that reason, they are afocal systems (i.e., the image of an object placed at infinity is also formed at infinity, meaning that the rays enter parallel to the telescope, and are also parallel at the exit of the instrument), permitting the eye of the observer to work without accommodation.

In the most simplistic configuration, these instruments are essentially composed of two main elements: two lenses placed one after the other, working as objective and eyepiece, respectively.

2.1 Kepler's Telescope

The simplest telescope design is the so-called astronomical or Keplerian telescope. This instrument is composed of two convergent lenses working as objective (O, with a focal length of f'_{obj}) and eyepiece (E, with f'_e). The telescope is mounted in such a way that the distance between both lenses is equal to the addition of its focal lengths. This instrument sends an image of an object placed at infinity, to infinity, with a magnification $\Gamma = -f'_{obj}/f'_e$, flipping up-and-down and left-

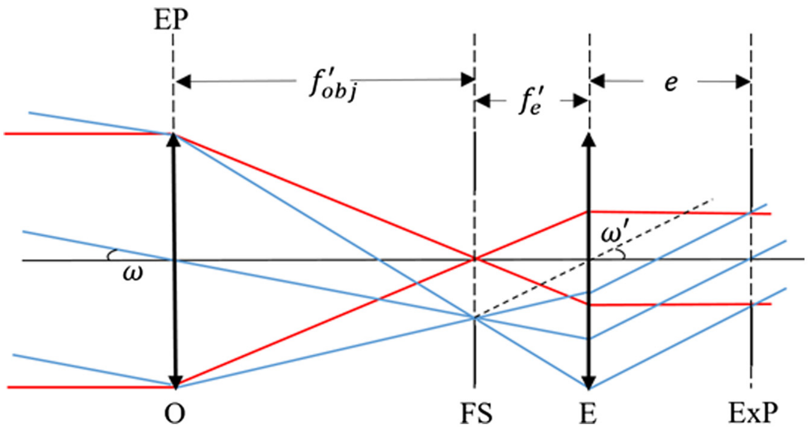


Fig. 3 Basic sketch of Kepler's telescope. The sketch shows on-axis (red) and with a certain half-field (blue) ω object ray tracing, the field stop (FS) and the entrance (EP) and exit (ExP) pupils. *e* is the ExP distance from the eyepiece.

to-right the resulting image with respect to the original observing object. A simple sketch of this design and its basic raytracing is shown in Fig. 3.

2.2 Galileo's Telescope

Another basic telescope design is the Galilean telescope. This design is composed of a convergent lens, which works as an objective, and a divergent lens as an eyepiece. The design is done in such a way that the focal plane of both lenses coincides (see Fig. 4). Thus, the exit pupil (ExP) in this instrument is placed between the lenses (i.e., the image of the entrance pupil, EP, is virtual), but the image is not inverted as in the previous case, thus: $\Gamma = f'_{obj}/f'_e$.

2.3 Resolution

Resolution is the ability of an optical system to distinguish between two close objects, and it is typically represented as the minimum resolvable angle between two observed objects. Resolution is affected both by diffraction and aberrations.

Generally speaking, optical aberrations (see Sec. 2.4) degrade images and affect image quality by reducing the contrast and resolution (a deeper review of aberrations is performed in the next section). On the other hand, resolution is limited by diffraction,[2] which consists of the blurring of sharp edges of an image made by a small aperture. For the case of an astronomical refractive telescope, the theoretical minimum resolvable angle is defined as follows:

$$\theta = \frac{1.22\lambda}{D_{EP}}, \tag{1}$$

with λ being the wavelength used for the observation and D_{EP} the diameter of the EP, which in several applications coincide with the diameter of the objective lens. This expression constitutes the so-called Rayleigh's resolution criterion.

It is important to note that this theoretical definition simply considers the diffraction caused by the physical dimensions of the lens, and no other limitations, such as optical aberrations, are considered. For this reason, it is important to define metrics to measure and determine experimentally the resolution of an optical instrument, considering the actual limitations such as geometrical aberrations, vignetting, manufacturing errors, or chromatic aberration.[1–3,19]

A common test used for measuring the resolution of an optical system is the so-called US Air Force (USAF) 1951 resolution test chart (see Fig. 5).

In this chart, features are arranged in elements and groups. Each element is made up of equally spaced bars (three horizontally and three vertically placed). Groups consist of six elements labeled from 1 to 6 (in increasing frequency).

Using the USAF-1951 chart, once the last element resolvable (i.e., the smallest element that can be clearly observed without confusion) with a given optical system is determined, the resolution r of such instrument is computed using the following expression:

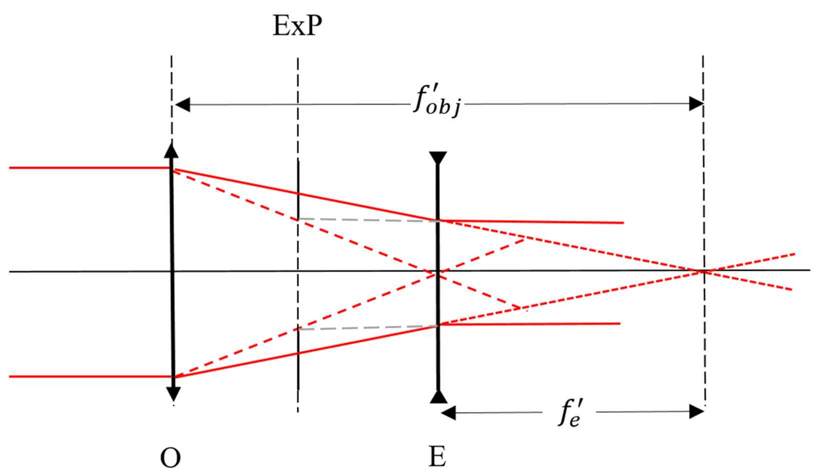


Fig. 4 Basic sketch of Galileo's telescope for an on-axis object. The ExP is virtual because it is the image of the objective through the eyepiece, which is a divergent lens.

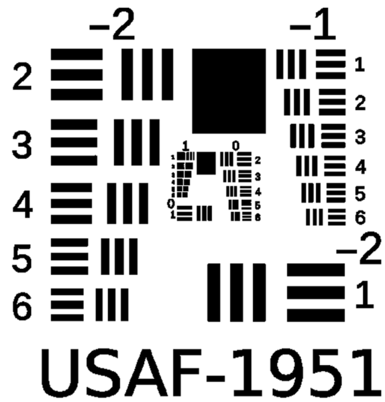


Fig. 5 USAF 1951 test chart. Using this reference, it is possible to measure the real spatial resolution of a given optical system.

$$\mathscr{r} = 2^{\left(\text{Group number}+\frac{\text{Element number}-1}{6}\right)}, \tag{2}$$

With this procedure, the resolution $\mathscr{r}$ of the optical system is determined in lp/mm. Using a calibrated chart, it is possible to express such magnitude as an angle θ_r and compare it with the theoretical value θ.

It is important to note that the ability to resolve details, particularly when dealing with resolution test charts, other factors such as magnification and the experience of the user, together with the illumination conditions, also affect the final performance of the instrument and the user observing experience. These issues will be addressed in other sections of this work.

2.4 Aberrations

Real optical lenses are thick and present curvature radii on their surfaces. Thus, the real ray tracing of an optical instrument presents some deviations from what is expected with paraxial approximation. Those differences are called geometrical (or monochromatic) aberrations. Such aberrations can be separated into two families: aberrations that deteriorate (or blur) the image, such as spherical aberration, and aberrations that distort the resulting image, such as field curvature. Moreover, the refractive index n of a given material varies as a function of the wavelength λ of the incoming light. If now we consider the basic formula for computing the focal length of a single lens immersed in the air (i.e., assuming a glass/air interface)[18]

$$\frac{1}{f'} = (n(\lambda) - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right), \tag{3}$$

where R_1 and R_2 refer to the curvature radii of the two surfaces of the lens (see Fig. 6), the dependence of the refractive index with the wavelength manifests the fact that different wavelengths will provide different values of the focal length. Thus, for instance, for common glass, the

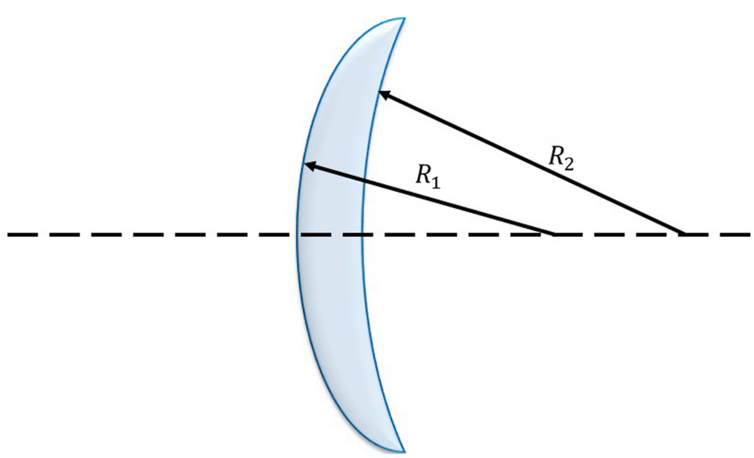


Fig. 6 Basic sketch notation for Eq. (3) for a typical positive meniscus lens.

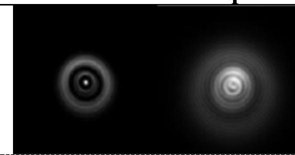
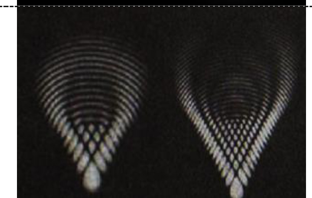
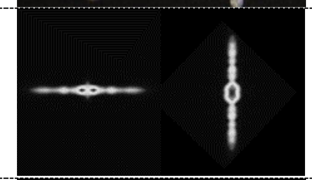
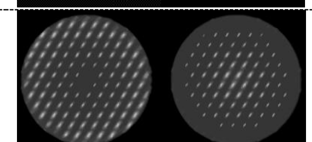
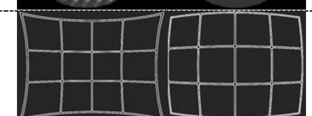
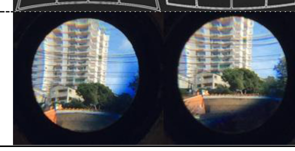
Name	Nature	Aberration examples
Spherical Aberration	Geometrical	
Coma	Geometrical	
Astigmatism	Geometrical	
Field Curvature	Geometrical	
Distortion	Geometrical	
Chromatic aberration	Chromatic	

Fig. 7 Most common optical aberrations.

resulting focal length when illuminating with monochromatic red light is larger than when using blue light.

Figure 7 shows a concise summary of the most relevant and common aberrations, as does Fig. 8. Those labeled geometrical natures correspond to the five primary aberrations also known as Seidel aberrations. The interested reader may be referred to Refs. 1, 2, 4, 19, and 20.

3 Description of the Practice

The guide to the laboratory works provides a summary and overview of geometrical optics and telescopes as has been carried out in previous sections. The students first must work with the JavaOptics[21] software for practice with the imaging process. They must work with a single flat convergent lens, and then, they put two together to design a Kepler's telescope. After doing that, a Galileo telescope is designed, and a more realistic simulation using thick lenses is done, emphasizing the aberration effects on the image formation process.

Next, the students move to a laboratory table with an optical bench and different lens supports. They must use a lensmeter to measure the power (i.e., the focal length) of several lenses. Then, they choose a pair of convergent lenses properly to get a Keplerian telescope with the desired magnification, and they observe through the eyepiece.

Next, a pupil stop (i.e., a diaphragm) is placed in different positions across the optical bench, to analyze the function of this element, depending on its relative position respective to the lenses. By closing the aperture of such elements, the students can also discuss the partial compensation of some aberrations such as field curvature.

The historical observations of Saturn carried out by Galileo Galilei are introduced to students, and some simulation examples (see Sec. 3.4) are discussed. Within this context, the students are then invited to recreate Galileo's observations in the laboratory. To do so, the students

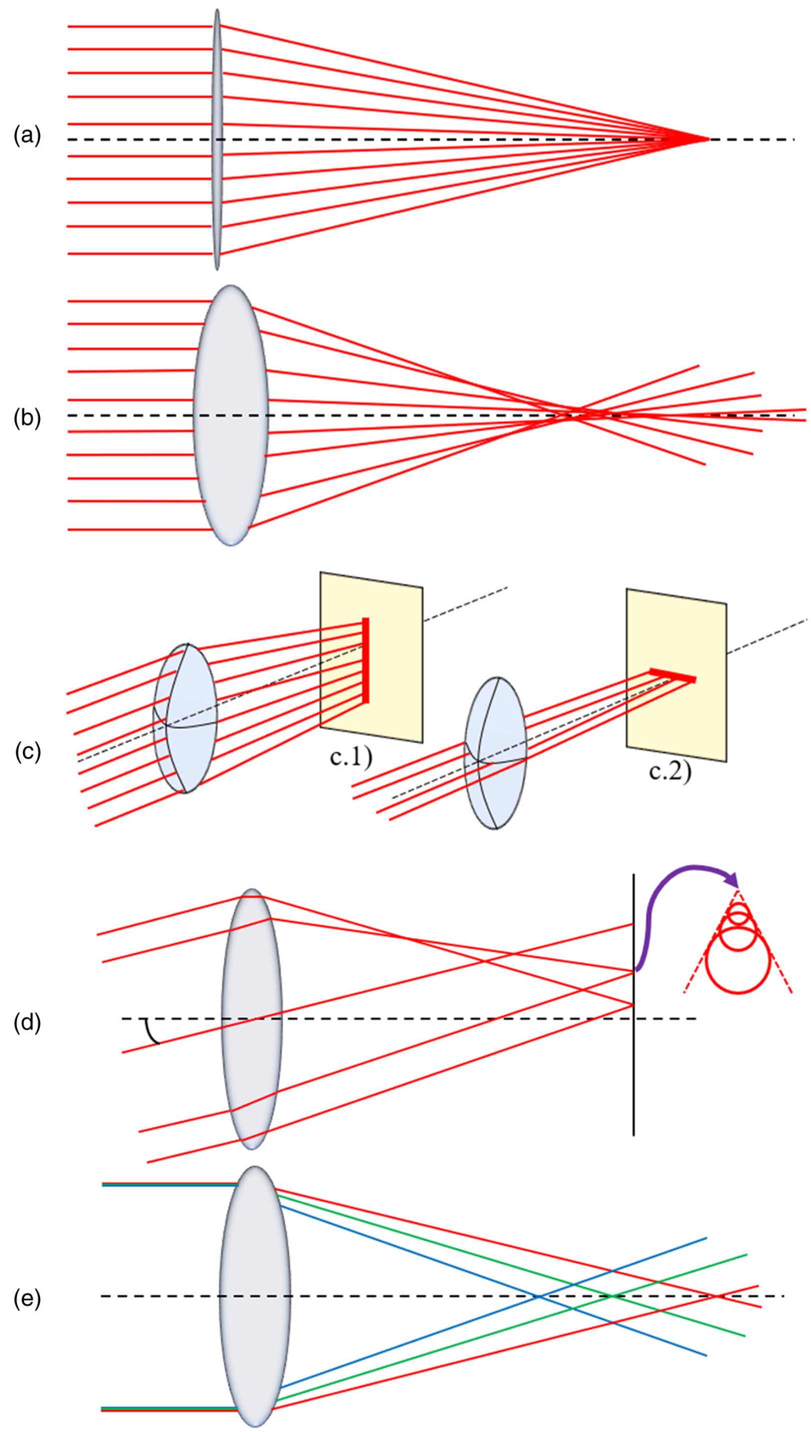


Fig. 8 Sketch of the ray tracing for a perfect thin lens with an object located at infinity over the optical axis (a), and a compendium of basic sketches for common aberrations: (b) spherical, (c) astigmatism, (d) coma, and (e) chromatic aberration.

built a simple telescope with similar characteristics to Galileo's, and they both observed a photographic sample of Saturn and a resolution chart, which were placed at infinity (i.e., at a long enough distance from the instrument, compared with the size of the elements and the focal length used).

Finally, with the same reference images (Saturn and the resolution USAF test), a comparison between this simple telescope (in which the objective lens and eyepiece are both singlets) and an achromatic doublet used as the objective is carried out and analyzed for different pupil diameters.

3.1 Photonics Laboratory Course

To put into context the hands-on experience presented in this work, this subsection summarizes the main characteristics of the course which was delivered until 2019.

Photonics Laboratory is a compulsory course for the master's degree in photonics at the Universitat Politècnica de Catalunya (UPC), the Universitat de Barcelona (UB), the Universitat Autònoma de Barcelona (UAB), and the Institut de Ciències Fotòniques (Photonics Science Institute, ICFO). It consists of five ECTS credits, and it is divided into 14 different laboratory experiences located in the three different universities that participate in the master's program (an updated version of the course syllabus for the academic year 2023–2024 can be found in Ref. 22, the practice described in this work is currently not being offered anymore). Each laboratory work comprises eight teaching hours, and students should select four of the subjects (choosing the topics that are of interest) and prepare a report for each of them. The laboratory works are taken in pairs of students.

This paper refers to a part that corresponds to the 75% of a laboratory work entitled "Dealing with resolution and magnification: telescopes and microscopes."

3.2 JavaOptics Course

The JavaOptics Course (JOptics) is an ensemble of Java applets and teaching resources for physical optics courses at the university level for physics of optics and optometry courses.[23] The course was developed by the members of the Optics and Photonics Research Group of the Applied Physics Department of the UB in the early 2000s thanks to three projects (DOGC-3453, 2003MQD-00138, and 11/III/MM-Eva/34/CARN), and the use of its resources for education purposes is open and free. It consists of a series of 13 Java applets that covers all the topics of a physical optics course, from geometrical optics and colorimetry to Fourier optics and optical tweezers.

Since its invention, the course has been used in the teaching of the subject of physical optics at the degree of physics of the UB, both in practical problems and homework assignments, and in the laboratory practices.[23–25]

In this experimental practice, students work with the "Ray Tracing" applet (see Fig. 9), which allows performing simulations of both paraxial lenses (the option used in this practice for the design of telescopes) and also real lenses by means of exact ray tracing using the thick lens equation.

Using this application, students analyze different situations and types of aberrations as the ones presented in Sec. 2.4.

3.3 Design and Construction of Basic Telescopes

Using the "Ray Tracing" app, students may design different telescopes. They should design both an astronomical (see Fig. 10) and a Galileo telescope (see Fig. 11).

After a preliminary design of both configurations, students are introduced to the use of a commercial lensmeter (see Figs. 12 and 13) to characterize a set of lenses (red box in Fig. 12). With those lenses, students might try to build in an optical bench the telescopes that they have designed using the JOptics application.

3.4 Galileo's Recreation

As previously stated, students are invited to recreate Galileo's early observations both with simulations and experimentally. Regarding simulations, a simple Gaussian blurring with commercial programs, such as Photoshop®, allows the recreation in the computer of the type of images that Galileo might have seen through his instrument in the 1610s (see Figs. 14 and 15).

This simple computational experiment allows the students to think about how the lack of optical quality and magnification affected Galileo's observations and his interpretation.

Then, using the set of lenses that match Galileo's design (in terms of magnification, according to Ref. 11) and a corrected system, the observation of a high-contrast photographic plate with Saturn's image is performed by the students, allowing them to recreate both Galileo's (see Fig. 16) and Huygens' observations.

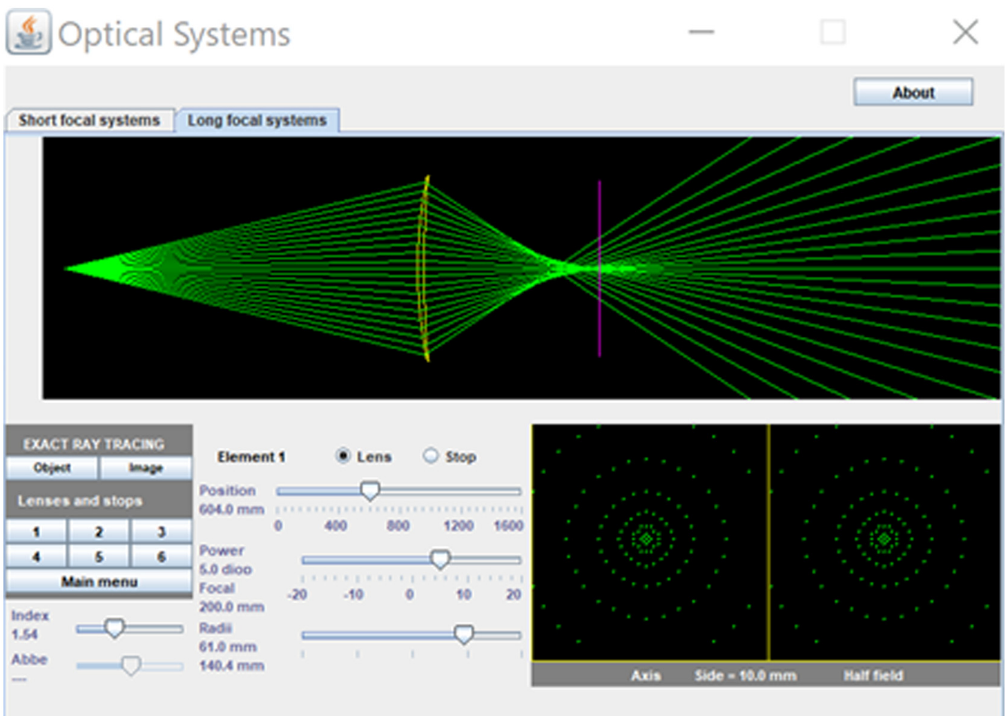


Fig. 9 Screenshot example of Ray Tracing applet user interface. In this window, the user can analyze the aberrations thanks to the spot diagram at the image plane by means of exact ray tracing calculation. The applet permits both the design of short (e.g., in the case of microscopes) and long (e.g., telescopes) focal length systems. The user can introduce a maximum of six elements (lenses and/or stops). In the example shown in this figure, it is possible to set the curvature radii of the lenses used.

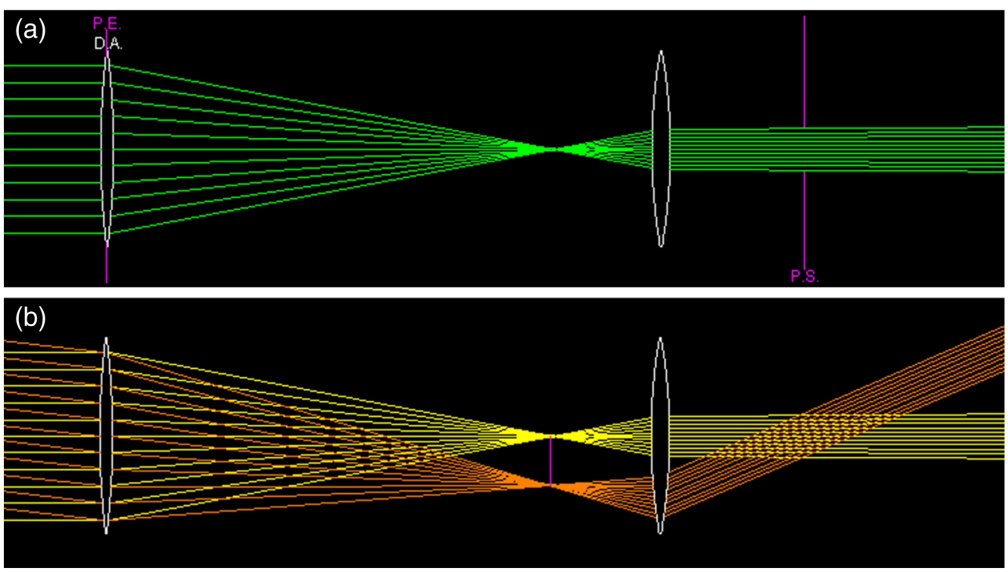


Fig. 10 Ray tracing simulation for a Kepler's telescope [(a) on-axis object; (b) off-axis object] with an objective of 1.5 D and an eyepiece of 5.9 D, giving a total magnification of $\Gamma_K \approx 3.93\times$. The half-field is 1.6 deg. P.E and P.S refer to EP and ExP in Catalan, respectively.

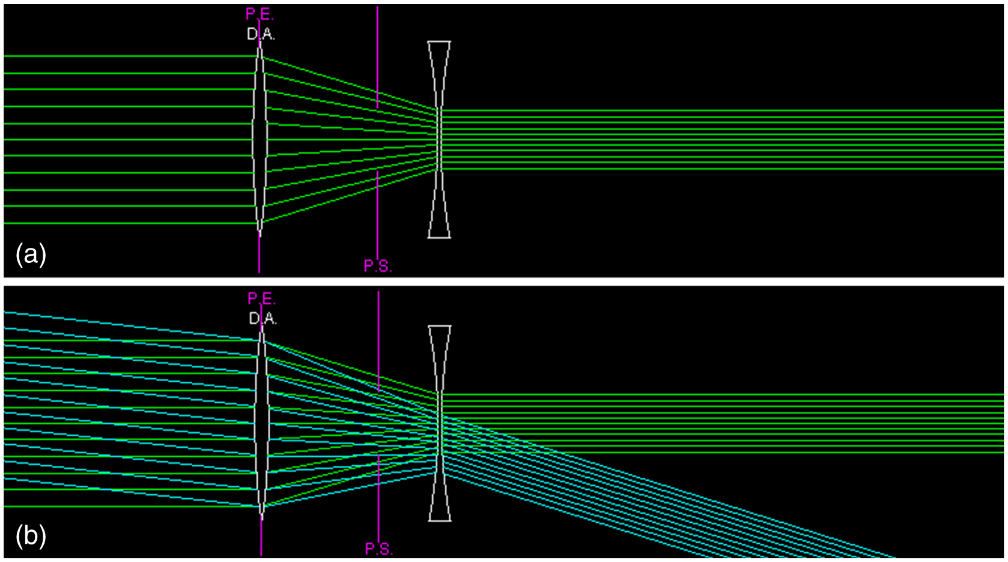


Fig. 11 Ray tracing simulation for Galileo's telescope [(a) on-axis object; (b) off-axis object] with an objective of 2.4 D and an eyepiece of −6.8 D, giving a total magnification of $\Gamma_G \approx 2.83\times$. The half-field is 1.6 deg. P.E and P.S refer to EP and ExP in Catalan, respectively.

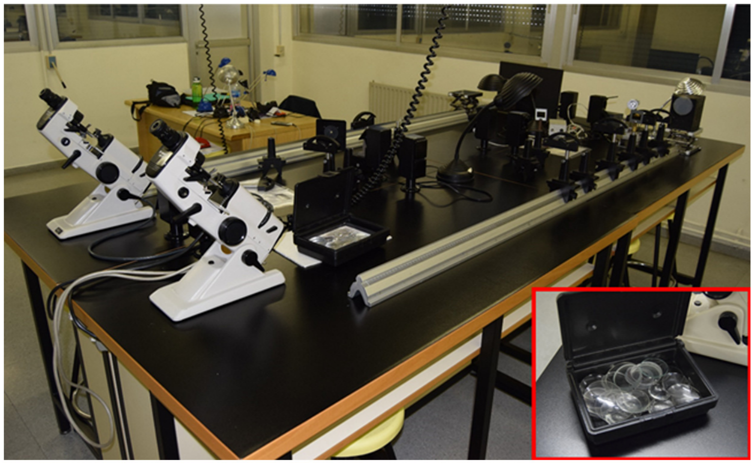


Fig. 12 Optical tables where the students perform the experiment. The different materials that the students have are optical bench, lensmeters, sets of convergent and divergent lenses to characterize (see the red box on the bottom-right corner of the image), and different supports for lenses and other auxiliary material (e.g., screens, transparencies, lamps, and diaphragms).

4 Results

In this section, the results of the practice are presented. First, the main results are shown and interpreted, and then, a collection of results obtained by students is presented.

4.1 Results of the Practice

Assuming $\lambda = 550$ nm, $f'_{obj} = 500$ mm, and considering the two cases for objective aperture ϕ (50 and 25 mm), using Eq. (1), the theoretical resolution corresponds to 2.75 arcsec for $\phi = 50$ mm and 5.53 arcsec for $\phi = 25$ mm.

The sample used to recreate Galileo's observations of Saturn presents two inner gaps (i.e., the distance between the inner ring and Saturn's surface) which measure 0.33 mm. Since the sample was placed at a distance of 18 m, the corresponding angle required to resolve the rings will be 3.78 arcsec (see Fig. 16).

(a) (b)

Fig. 13 Examples of students during the practice: characterizing lenses with the lensmeter (a) and observing distant objects with the instrument that they have built (b).

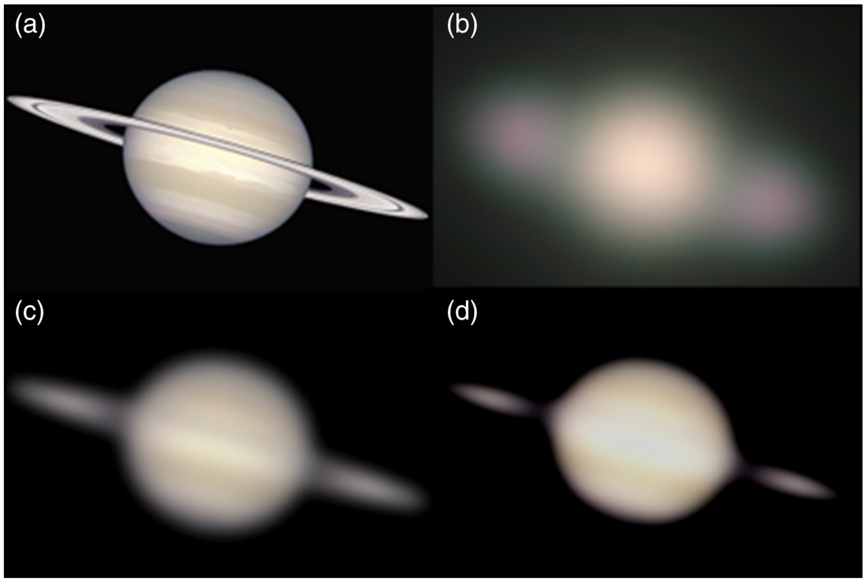


Fig. 14 Recreation of Galileo's observations of Saturn's rings using a commercial program for photography editing: (a) reference image and (b)–(d) images obtained with different levels of Gaussian defocusing.

The minimum magnification required by the telescope to resolve the gaps, assuming 1 arcmin for the resolution for the eye, will be $60/3.78 = 15.87\times$.

Students used a Keplerian telescope formed by an eyepiece of approximately +30D ($f'_e = 33.33$ mm), together with an objective lens of 500 mm (+2D), providing a theoretical total magnification of $15 \pm 2\times$ (very close to one of Galileo's telescopes as presented in Ref. 11).

This configuration allows us to distinguish the gap between Saturn's main body and the rings.

4.2 Students' Results

In this subsection, we present the results obtained by the students when using a Keplerian telescope of 15× with the different four configurations shown in Fig. 17: an achromatic doublet or a singlet meniscus lens as the objective lens and two different sizes for the EP. The results obtained

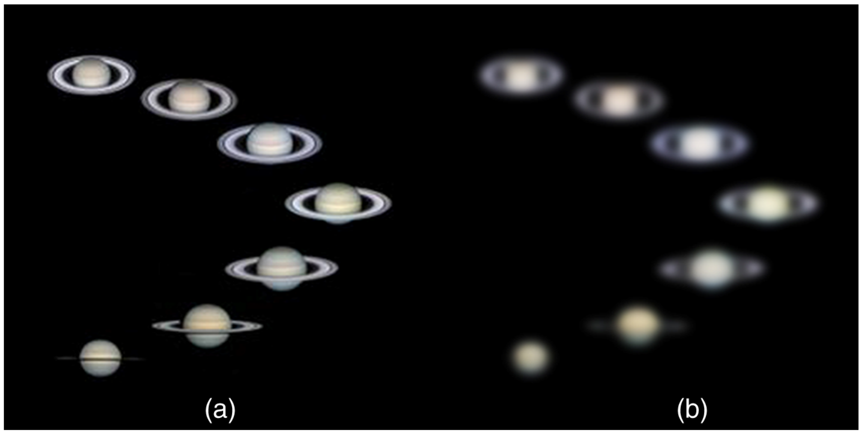


Fig. 15 Recreation of Galileo's observations of Saturn's rings for different phases of the rings using a commercial program for photography editing: (a) reference image and (b) blurring with Gaussian defocusing.

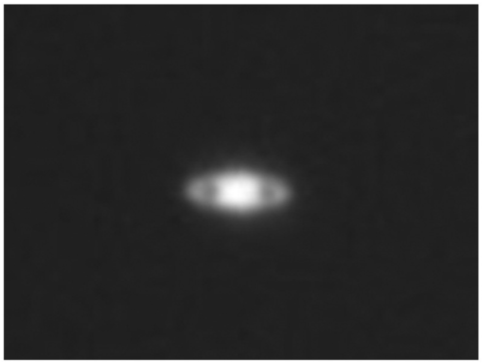


Fig. 16 Image of Saturn obtained with one of the telescopes, with an achromatic doublet as an objective lens, developed in the practice. The handles are clearly observed in the image.

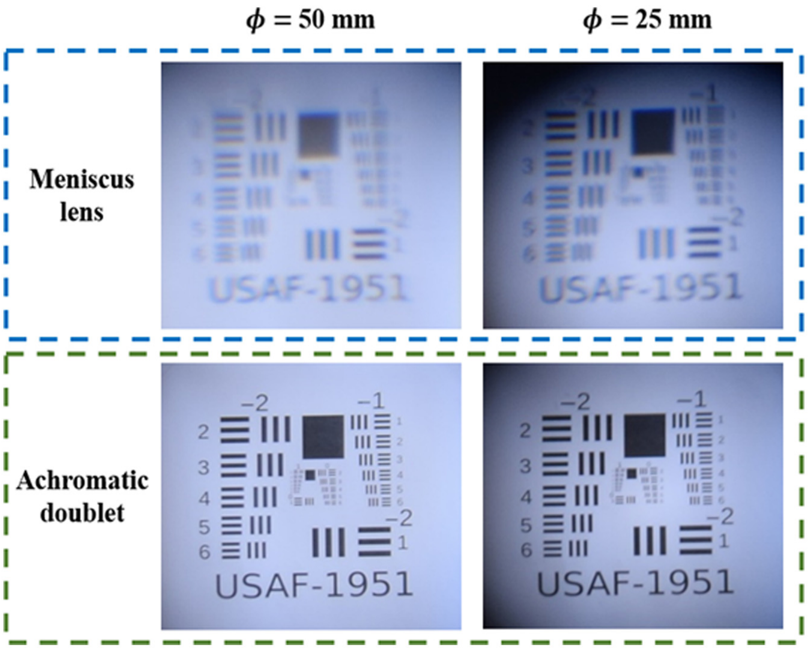


Fig. 17 Color images of the USAF test obtained with the different systems used.

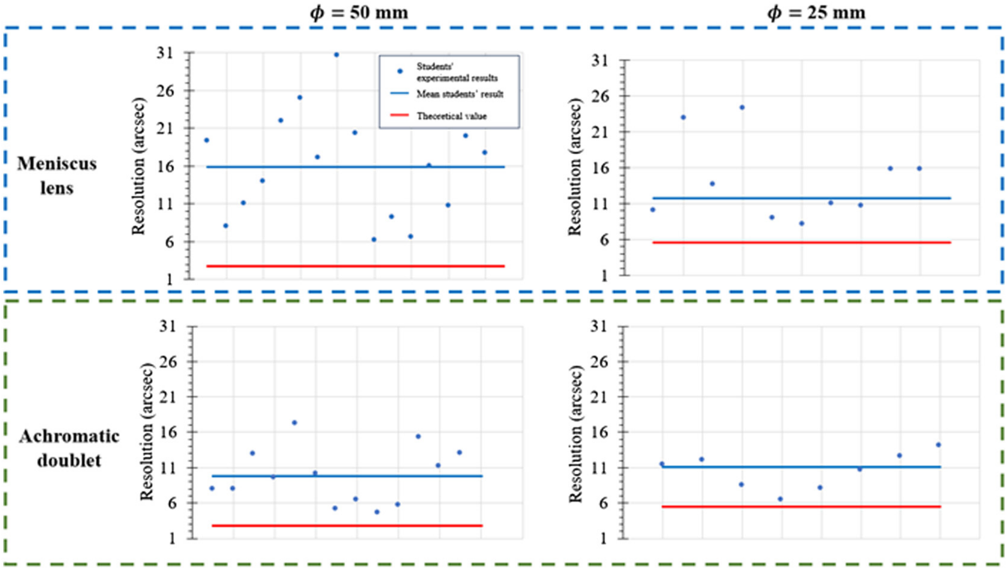


Fig. 18 Results of the resolution obtained with the different combinations by student pairs. The blue dots represent the values of the angle θ_r obtained by the students, in different trials; the blue line corresponds to the mean value of such collection of results, and the red line represents the theoretical resolution in every case, obtained by diffraction (i.e., θ).

by the students are shown in Fig. 18 for all these different cases and compared with the theoretical values obtained with diffraction theory. As can be seen in Fig. 18, students never do as well as the theoretical value.

5 Discussion

In this section, the results presented in the previous section and the educational interest of this practice are discussed.

5.1 Results Discussion

As explained in Sec. 4.1, a theoretical minimum magnification of around 15× was required to resolve Saturn's sample rings, and such magnification was used as a reference for the tests. Although the rings' gaps can be inferred in Fig. 16, the quality of the resulting image is quite poor, and the results obtained by the students (see Fig. 18) are still far from the theoretical values (5.53 arcsec with the smallest aperture and 2.75 arcsec with the larger one). These results show how the limitations of real optical systems arise in practice, making the results differ with respect to the expected values.

The professors, with greater expertise than students, when dealing with the observation of test charts through optical systems, were able to resolve up to 4.24 arcsec using the achromatic doublet with $\phi = 50$ mm. This value is almost two times the reference minimum resolvable angle expected with diffraction theory. Thus, despite the achromatic correction, the diffraction limit is not reached.

It must be pointed out that the so-called Rayleigh resolution criterion[2] is based on the analysis of the Airy discs produced by the Fraunhofer diffraction of two bright points.[2,4,7] When considering a test bar, the convolution of the aforementioned disk by the bar function gives an extra component more dependent on the black and white bars contrast.[26] An interesting experiment to explore these issues is presented in Ref. 27. Moreover, an achromatic doublet, despite making it easier to distinguish the edges of the bars due to its correction (as is shown in Fig. 17), could still present geometrical aberrations.

This is proven by the fact that, despite the diffraction theory usually being presented in class as the limit of resolution of an optical system, the magnification and illumination conditions have to be taken into account as well, together with the characteristics of the chosen test chart. In addition, the reference value of 1 arcmin for the resolution of the eye is a typical value, which will be different depending on the user's eye and their visual impairments.

In addition, the lack of proper alignment, the stray light coming from the surroundings (such as other tables of the laboratory or the corridor), and deficient focusing also affect the resolving capabilities of the users, and therefore, the final experimental result is obtained.

Furthermore, the huge disparity of results can be explained by several aspects related to the subjective expertise and experience of the user, such as lack of concentration at the end of the practice, lack of dark adaptation of the eye, or being in an awkward and uncomfortable position when observing, which will prevent relaxed sight [issues such as the importance of being comfortable when observing through an optical instrument (in this case, a telescope) or the necessity to a proper adaptation to darkness, had been widely reported by observers, both professional and amateurs]. Interesting notes on this subject can be found in Ref. 28.

5.2 Educational Interest of the Experience

The practical experience presented in this paper shows the students how the real manufacturing and use of optical instruments differ from the theoretical and ideal calculations.

With the workshop presented here, students are brought through the whole process between the basic design of simple optical instruments to dealing with the construction and analysis of the performance of the final instrument. Of course, an important part of the real optical design and engineering job is the tolerancing analysis of the optomechanical system, but this issue is expected to be analyzed at more advanced stages of the career of the students' sample of the present work. In addition, a historical example has been exposed as a motivation for the students to start working on the topic.

The limitations of technology and scientific instruments in any particular era have affected the development and advancement of different scientific fields, impacting discoveries at any particular moment in history and changing mindsets and prevailing paradigms. Therefore, there is a direct correlation between the development of the technologies that provide such instruments and the advancement of science,[5–8] as the examples of the invention of the microscope and the telescope illustrate this impact on the fields of biology and astronomy, among others. This implies that the study of the technological limitations of a given era can provide a better knowledge of how certain ideas and scientific fields have evolved in history.[8,29]

This fact, despite having its own interest in the field of history of science, can also prove a good example to students about how the factual material developments and manufacturing technologies affect both the experimental results and the conclusions and ideas that can be obtained from such experiments, showing students the gap between the theoretical and more "academic" concepts and the reality and experimental or practical implementation, as well as how to bridge it.

6 Conclusions

An experimental workshop in optical resolution for telescopes, inspired by the limitations of Galileo's telescopes in his early observations of Saturn rings, has been presented. A complete summary of the historical background, motivation, and basic theoretical concepts for performing such workshops has been presented, together with a guide to develop the experience and results obtained with students. The discussion of these results and the implications of this experience on the formation of optics and photonics students have been also presented.

The authors strongly believe that both the experimental implementation and the comparison with historical examples can have a great impact on a student's personal learning experience, as stated both in the present paper and in previous works. In addition, student experience and feedback, despite their different backgrounds and interests, have been positive in all editions.

The authors hope that this article will be an interesting tool for lecturers in optics, photonics and optical design, and engineering to introduce and motivate their students to the design and manufacturing of optical instrument and will be used to develop similar experiences.

Code and Data Availability

The data utilized in this study were obtained by the students and the authors themselves during the practical workshop described in the text. Data are available from the authors upon request.

Acknowledgments

The authors want to acknowledge all the students who have participated in the course across the different editions of it, with special mention to the ones who allowed their images to appear in Fig. 13. Authors also want to thank Miss Siobhán Henry for revision of the text and to Dr. Matthew Jungwirth for the invitation to present this work in this special section of *Optical Engineering*. The authors are grateful to the reviewers for their corrections and suggestions.

References

1. W. J. Smith, *Modern Optical Engineering*, McGraw-Hill, New York (1998).
2. M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, Cambridge University Press (1999).
3. B. K. Johnson, *Optics and Optical Instruments*, Dover Publications, Inc., New York (1960).
4. V. J. Mahajan, *Aberration Theory Made Simple*, SPIE Press, Bellingham, Washington (1991).
5. W. E. Burns, *The Scientific Revolution in Global Perspective*, Oxford University Press (2015).
6. A. van Helden, *The Invention of the Telescope*, The American Philosophical Society, Philadelphia, Pennsylvania (1977).
7. M. I. Cross and M. J. Cole, *Modern Microscopy. A Handbook for Beginners and Students*, Chicago Medical Book Company, Chicago, Illinois (1912).
8. A. Marzoa and S. Vallmitjana, "Image quality analysis of an antique microscope objective with a Shack-Hartmann wavefront sensor: an experiment of educational interest," *Opt. Pura Appl.* **54** (2) 1–18 (2021).
9. https://www.photonics.masters.upc.edu/en.
10. A. Marzoa and S. Vallmitjana, "Understanding resolution with Galileo's telescopes," in *Educ. and Training in Opt. & Photonics Conf.* (2021).
11. V. Greco, G. Molesini, and F. Quercioli, "Telescopes of Galileo," *App. Opt.* **32** (31), 6219–6226 (1993).
12. I. Juvells and R. M. Moliné, "Els primers telescopis de Galileu. Consideracions sobre els seus orígens i trets característics," *Rev. Fís.* **4**, 6 (2009).
13. L. Fermi and G. Bernardini, *Galileo and the Scientific Revolution*, Dover Publications (2013).
14. A. Koyre, "Galileo and the scientific revolution of the seventeenth century," *Philos. Rev.* **52**(4), 333–348 (1943).
15. A. van Helden, "Saturn and his Anses," *J. Hist. Astron.* **5**, 105–121 (1974).
16. E. A. Partridge and H. C. Whitaker, "Galileo's work on Saturn's rings," *Pop. Astron.* **3**, 408–414 (1987).
17. A. Marzoa, "Galileo y las orejas de Saturno: la importancia de la resolución," *Astronomía* **275**, 30–37 (2022).
18. C. Huygens, *Systema Saturnium, sive de causis mirandorum Saturni phaenomenon, et comite ejus planeta novo*, Adrian Vlacq, The Hague (1659).
19. E. Hecht, *Optics*, Pearson Education (2016).
20. L. Lakshminarayanan, "Zernike polynomials: a guide," *J. Mod. Opt.* **58**, 545–561 (2011).
21. http://www.ub.edu/javaoptics/index-en.html.
22. https://www.photonics.masters.upc.edu/en/curriculum-2023-24.
23. A. Carnicer et al., "An on-line applet-based optics course for undergraduate students," *Proc. SPIE* **4829**, 23–24 (2004).
24. A. Carnicer et al., "Monitoring learning by means of trace analysis in an optical trapping simulation," *Opt. Pura Apl.* **43**(2) 119–125 (2010).
25. J. Mas et al., "Understanding optical trapping phenomena: a simulation for undergraduates," *IEEE Trans. Educ.* **54**(1), 133–140 (2011).
26. J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, Berkshire (1998).
27. C. Leung and T. D. Donnelly, "Measuring the spatial resolution of an optical system in an undergraduate optics laboratory," *Am. J. Phys.* **85** (6) 429–438 (2017).
28. https://starizona.com/blogs/tutorials/observing-tips.
29. S. Vallmitjana, C. Ferran, and S. Bosch, "Non-contact technique for testing antique optical instruments based on wavefront sensing," *J. Mod. Opt.* **58**(14), 1269–1277 (2010).

Antonio Marzoa is an assistant professor at the Universitat Politècnica de Catalunya (UPC), where he lectures and performs research in astrophysics and molecular dynamics, and a research engineer at SENER Aeroespacial, S.A., where he carries out applied research in optics for astronomy, metrology, healthcare, and fusion projects in the private sector. He received his BSc degree in physics from the Universitat de Barcelona (UB) in 2016, his MSc degree in photonics from the UPC in 2017, and his MSc degree in astrophysics from the Valencian International University (VIU) in 2023. He has been engaging in several fields related to optics and photonics, from optical metrology to visual optics, laser material processing, and optical tweezers, since 2014. He also collaborated in the curacy of the Collection of

Antique Scientific Instruments of the Faculty of Physics of the UB and its scientific heritage. He is also a member of the Spanish Royal Physical Society (RSEF), the Spanish Optical Society (SEDOPTICA), and the Catalan Physical Society (SCF) and has been involved in several outreach activities and associations. He is the author or co-author of 11 research and proceedings articles and has 40 contributions to national and international conferences in the fields of optics, history of science, astrophysics, and education.

Santiago Vallmitjana is an emeritus full professor of optics at the Applied Physics Department of the Faculty of Physics of the UB. He received both his BSc and PhD degrees in physics from the UB in 1972 and 1980, respectively. He has been engaging in several areas such as image quality analysis, holography, optical information processing, 3D optical pattern recognition, and applications on biological images. His latest current interests are beam shaping, wave-front coding, eye aberration study by interferometric analysis, and also the history of science and technology with special emphasis on scientific instruments. He is the author/co-author of ∼100 scientific papers and ∼250 conference communications related to optics and photonics and the history of science. He has been the curator of the Scientific Instruments Collection of the Faculty of Physics and a member of the Staff of the Virtual Museum of the University of Barcelona. He has served as the secretary and later the vice dean of his faculty. Concerning scientific societies, he is a senior member and fellow of SPIE, a senior member of Optica (formerly OSA, Optical Society of America), and a member of European Optical Society (EOS), AERFAI, UNIVERSEUM (the European Academic Heritage Network), the RSEF, the SCFís, and the Catalan Society of History of Science and Technology (SCHCT). He is also a member of SEDOPTICA where he was the president from 2015 to 2017.