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History of science and science combined: solving a historical problem in optics—the case of Galileo and his telescope

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Abstract The claim that Galileo Galilei (1564–1642) transformed the spyglass into an astronomical instrument has never been disputed and is considered a historical fact. However, the question what was the procedure which Galileo followed is moot, for he did not disclose his research method. On the traditional view, Galileo was guided by experience, more precisely, systematized experience, which was current among northern Italian artisans and men of science. In other words, it was a trial-and-error procedure—no theory was involved. A scientific analysis of the optical properties of Galileo's first improved spyglass shows that his procedure could not have been an informed extension of the traditional optics of spectacles. We argue that most likely Galileo realized that the objective and the eyepiece form a system and proceeded accordingly.

1 The principal issue

Consider the following uncontroversial historical data[1]:

– In early 1609 several astronomers, mathematicians, and practitioners trained the newly invented spyglass on the heavens.

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[1] For background discussion, see Bucciantini (2015), Smith (2014), Van Helden (1977), Van Helden (2010), Reeves (2008), Biagioli (2006), Zik and Hon (2012). Greco et al. (1993).

- Distinguished scholars did not know how the spyglass magnifies.
- Artisans were at a loss to improve the performance of the spyglass.[2]
- The available optical knowledge fell short of accounting for the essential optical phenomena (e.g., refraction).
- The available tools and methods were not suitable for solving technical problems involved in the production of adequate lenses and combinations of lenses (Van Helden 1977, pp. 47–48, 50–51; Bedini 1966, 1967).
- Notwithstanding these difficulties and limitations, Galileo made an astounding progress in a relatively short time in improving the magnifying power of the spyglass. In fact, he turned the spyglass into a telescope—a scientific instrument.
- From summer 1609 to January 1610, Galileo produced several telescopes that magnified in the range of 8 to 30 times.
- Historical and optical data of the telescopes attributed to Galileo show that the telescope that magnified about 14 times had a convex lens of 0.752 diopter for the objective and concave lens of 10.64 diopter for the eyepiece (1330 and 94 mm, respectively). The telescope that magnified about 21 times had a convex lens of 1.02 diopter for the objective and (non-original) biconcave lens of 21 diopter for the eyepiece (980 and 47.5 mm, respectively).[3]
- Galileo's contemporaries were able to refine their own instruments only after examining a device made by Galileo or receiving information about such devices either directly from Galileo or through a third party.

How do we understand these historical data? Evidently, Galileo unlocked the secret of the spyglass and kept this knowledge to himself. This knowledge had immediate practical consequences. The extant telescopes attributed to Galileo show clearly that the convex (objective) lenses had long focal lengths and the concave (eyepiece) lenses had short focal lengths; in other words, the objective lenses were weak, while the eyepiece lenses were extremely powerful. These are undisputed facts.

But what was Galileo's procedure? We turn to the secondary literature. According to the traditional view, Galileo was guided by experience, more precisely, systematized experience, which was current among northern Italian artisans and men of science. On this view Galileo realized that he would need a weak convex lens (objective) to "bring" far away objects closer, and a concave lens (eyepiece) to sharpen the image.[4] Here is a concise formulation of this position:

> With the procedure of the spectacle makers at hand, ... [Galileo] would have quickly found out, by trying several convex lenses in combination with a standard

[2] See, e.g., Ilardi (2007, pp. 224–235), Molesini and Greco (1996, pp. 425–427), Willach (2008, pp. 49–55, 82–89).

[3] The telescope that magnified about 30 times had a convex lens of 0.585 diopter for the objective and, according to our computations, its (lost) concave lens should have had 17.54 diopter for the eyepiece (1710 and 57 mm, respectively). For details of Galileo's telescopes, see http://catalogue.museogalileo.it/section/TelescopeObservingMeasuringAstronomicalPhenomena.html.

[4] On the functions of concave and convex lenses as visual aids, see Della Porta (1589/1650, Bk. 17, Chap. 10, p. 594), Della Porta (1658/1957, p. 368). Dupré (2005, pp. 174–179), Bucciantini (2015, pp. 53–79, espec. p. 66).

concave lens, that convex lenses with longer focal lengths resulted in higher magnification (Dupré 2005, p. 179).

Galileo's methodology—so this argument goes—was an educated extrapolation within the framework of spectacle optics. Presumably, the craftsmen in the market would have advised him to go for a weaker objective with a standard eyepiece, for the eyepiece was merely a sharpening lens, to make the image created by the objective lens sharp. This point is most important and worth amplifying. Galileo, like his contemporary perspectivists, did not consider the two lenses a system, that is, the eyepiece did not play a role in the magnification; it was applied for the sole purpose of sharpening the image formed by the objective. We note further that the traditional position takes account of the pace of discovery: "[Galileo] would ... quickly found out" the solution to the problem in a trial-and-error mode. This claim is made to comply with the historical evidence: Within less than half a year, Galileo made an astounding progress.

Now, what are the consequences of this position? If one wanted to improve the performance of the spyglass on these optical assumptions, namely, the objective enlarges and creates an image and the eyepiece sharpens it, what would one do? We proceed to spell out, step by step, the operative claim, "trying several convex lenses [i.e., objective] in combination with a standard concave lens [i.e., eyepiece]" with the discovery "that convex lenses with longer focal lengths resulted in higher magnification." The set, then, consists of one standard eyepiece and several objectives with increasing focal lengths. We have conducted the corresponding optical calculations. A common spyglass made of convex lens (objective) of about 1.5 diopter and concave lens (eyepiece) of about 5 dioper would yield magnification of about 3.3 times (Van Helden 1977, pp. 11–12; Ilardi 2007, pp. 224–235; Zik and Hon 2014, pp. 2–4). If one would be lucky to find an objective lens of 1 dioper, the spyglass then will magnify about 5 times. To obtain spyglasses that magnify 10 and 20 times, one would have to get objectives of 0.5 dioper and 0.25 dioper, respectively. These kinds of convex lenses have no effect in correcting visual deficiencies. For this reason, they were not in demand in the markets and, in any event, at that time lens makers were not able to produce such lenses. Galileo had to procure them himself.

Given the assumptions of the traditional view, and with a standard concave eyepiece at hand, Galileo would be expected to produce objective of about 0.36 diopter (efl = 2800 mm) to get magnification of 14 times; objective of about 0.25 dioper (efl = 4000 mm) to get magnification of 20 times; and objective of about 0.166 dioper (efl = 6000 mm) to get magnification of 30 times. Leaving aside the production and availability of such lenses, the traditional view suggests that Galileo would have sought convex lenses with increasing focal lengths, while keeping all the time of the trial and error exercise the same standard concave lens. After all, it is applied just for the purpose of sharpening the image created by the objective.

We disagree. There are essentially two principal, closely related objections which we may characterize as (1) scientific, and (2) historical.

(1) All of the telescopes resulting from the (presumed) trial-and-error approach have the same aperture, but different lengths. Dividing the focal length by the diameter of the aperture yields the focal ratio of the telescope. Longer focal ratio of a telescope provides more magnification with the same eyepiece, but less field of

view. It also affects the telescope's capacity for light gathering, reducing the contrast and degrading the quality of the image. In short, given the technological constraints at the time, and the absence of objective lenses of substantially larger apertures, these optical devices would be useless for astronomical observations.[5]

(2) The optical properties of the telescopes attributed to Galileo (which are extant) do not comply with the assumptions presupposed by the traditional view. The telescope that magnifies about 21 times had an objective lens of about 1.02 dioper and an eyepiece of 21 dioper (980 and 47.5 mm, respectively)—far from being "standard" (Zik and Hon 2012, pp. 440–441). It is evident that Galileo turned his attention to the other element in the set of lenses, namely, the eyepiece. Galileo produced near to standard objective lens and an immensely powerful eyepiece which were not available in the markets. To put it bluntly, while the traditional view holds that Galileo kept the eyepiece standard and tried, in a trial-and-error fashion, different weak objective lenses, the historical evidence shows precisely the opposite. To comply with the evidence Galileo must have done the reverse: increasing substantially the power of the eyepiece, while keeping a standard weak objective. In other words, Galileo realized that in order to improve performance he had to consider the two lenses a system and not a single lens (objective) whose image should be sharpened (eyepiece).

Add now to the scientific and historical objections the issue of confidence. Conducting a trial-and-error procedure requires confidence that one is on the right way to discovery. Suppose Galileo "kept trying"; it is, so to speak, a long way from 5 diopter to 21 diopter to obtain a lens combination that magnifies 20 times. What did keep Galileo's confidence that there will be a power that will eventually work? And recall that he was going, as it were, in the opposite direction. Based on the traditional view the craftsmen in the market would have advised him to go for a weaker objective with a standard eyepiece. Galileo's practice must have been seen at the time totally counterintuitive, against the systematized experience which was current among northern Italian artisans and men of science.

We align history of science with the science of optics. A scientific analysis of the optical properties of Galileo's first improved spyglass shows that his procedure could not have been an informed extension of the traditional optics of spectacles—the perspectivist's position. It is most likely that Galileo realized that the eyepiece is not for sharpening the image of the objective; rather, it takes part—as an element in a system—in the magnifying process. Optical magnification has nothing to do with image formation, image resolution, or visual perception; it is a geometrical relation between linear magnitudes and apparent angles.

2 Scientific analysis

Let us now examine a contemporaneous report on Galileo's spyglass. On August 21, 1609, Galileo publicly displayed his newly improved spyglass at the Tower of St. Mark

[5] On the different optical principles underlying spectacles and telescopes, see Zik and Hon (2014, pp. 8–11). On the mathematical formulation of the telescope, see Smith (1990, pp. 235–252).

to a group of distinguished Venetians. Antonio Priuli, who attended the presentation, described the instrument Galileo had used.[6] The optical properties of this telescope are,[7]

(D_1) Two lenses: one convex and the other concave.
(D_2) The diameter of the tube is about 42 mm.
(D_3) The overall length of the telescope is about 600 mm.
(D_4) The instrument magnifies nine times.

On the traditional view, Galileo applied the practice of spectacle makers which presupposed the following principles and rules:

(R_1) Convex lenses determine magnification.
(R_2) The concave eyepiece has no focal length; it does not play any role in magnification; its role is to sharpen the image.
(R_3) The standard spectacle lenses available at the time, whether convex or concave, varied between 1.5 diopter to about 5 diopter (i.e., 666 and 200 mm, respectively).
(R_4) Try several convex lenses in combination with a *standard* concave lens, and find by trial and error that convex lenses with *longer focal lengths* offer higher magnification.

Given R_1–R_4 and using *OSLO*,[8] the optical properties of a Galilean telescope that magnifies nine times should be,

(OR_1) Standard concave eyepiece of 5 diopter (efl = 200 mm).
(OR_2) Convex objective of 0.55 diopter (efl = 1800 mm).
(OR_3) The overall length of the telescope for viewing infinite objects is 1.6 meters.

The graph in Fig. 1 presents the mathematical relations between the optical powers of various lens combinations (i.e., eyepieces and objectives) producing Galilean telescopes that magnify 9 times. It comprises the following parameters: (1) the abscissa, objective power in diopter; (2) the ordinates (left): eyepiece power in diopter; and (3) the ordinates (right): the overall length of the instrument in meters for viewing infinite objects. Clearly, one could replace values OR_1 – OR_3 with the values of different lens combinations and, consequently, different overall lengths would be obtained. For example, the weaker the eyepiece, the weaker the objective should be, so an eyepiece

6 Favaro (1907, vol. 19, pp. 587–588): "Che era di banda, fodrato al di fuori di rassa gottonada cremesine, di longhezza tre quarte $^1/_2$ [about 60 cm] incirca et larghezza di uno scudo [about 4.2 cm], con due veri, uno ... cavo, l'altro no, per parte; con il quale, posto a un ochio e serando l'altro, ciasched'uno di noi vide distintamente, oltre Liza Fusina e Marghera, anco Chioza.... E poi da lui presentato in Collegio li 24 del medesimo, moltiplicando la vista con quello 9 volte più.... Presentato in Signoria il giorno d'heri un instrumento, che è un cannon di grossezza d'un scudo d'argento poco più e longhezza di manco d'un braccio [a braccio is about 66 cm], con due veri, l'uno per capo, che presentato all'cchio multiplica la vista nove volte di più dell'ordinario, che non era più stato veduto in Italia."

7 The keys used in the text are: D—data of Galileo's telescope; R—traditional view; OR—optical calculations of the traditional view; OD—optical calculations of the data; efl—effective focal length.

8 The computations throughout this paper were made with *OSLO* (Optical Software for Layout and Optimization) using the same glass properties as those of Galileo's telescope that magnified about 21 times: see Greco et al. (1993).

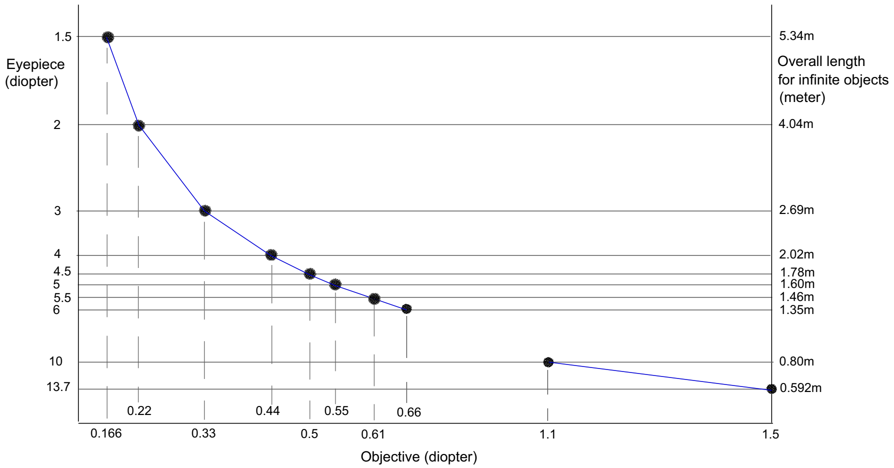

Fig. 1 The mathematical relations between the optical powers of various lens combinations

of 2 diopter (efl = 500 mm) and an objective of 0.22 diopter (efl = 4545 mm) will result in magnification of nine times and overall length of 4.04 m. However, we are constrained by R_2 and R_4 to use only standard concave eyepieces to obtain an instrument that magnifies nine times. All other possible combinations, be they OR_1 and OR_2 or other optical layouts given in Fig. 1, will result in instruments of substantially larger overall length than the length of the telescope which Galileo displayed in Venice.

We therefore claim that the telescope Galileo publicly displayed in Venice does not correspond to the telescope "constructed" according to the traditional view. No matter what lens combinations one may choose, rules $R_1 - R_4$ imposed a different optical scheme from the one Galileo used to improve the magnification of the telescope he displayed in Venice.

According to $D_1 - D_4$ and using *OSLO* the optical properties of the telescope Galileo displayed at Venice should be,[9]

(OD_1) Concave eyepiece of 13.7 diopter (efl = 73 mm).
(OD_2) Convex objective of 1.5 diopter (efl = 663 mm).

The overall length of a Galilean telescope is determined by the difference of the focal length of its lenses. Given $D_3 - D_4$, only lens combination OD_1 and OD_2 will comply with the required demand, that is, a significantly strong eyepiece with a standard (weak) objective. The implications are,

1. Contrary to the traditional view, an objective of 1.5 diopter is not a significantly *long-focal-length* lens.
2. Contrary to the traditional view, an eyepiece of 13.7 diopter is not a *standard* concave lens used for sharpening images.

[9] Even if the length of the tube as reported by Priuli had some uncertainties, a tolerance of ±100 mm will not affect the core of our claim. For a tube of 700 mm, an eyepiece of about 12 diopter (efl = 83.3 mm) would be necessary to obtain magnification of 9 times. For a tube of 500 mm an eyepiece of abuot 16.4 diopter (efl = 61 mm) would yield magnification of 9 times.

3. The specifications of the objective used by Galileo fit well with the common weak convex lenses available at the spectacle market.

This analysis excludes the procedure suggested by the traditional view.

3 Conclusion

At the time, many talented men of science were trying to improve the new device and failed (Van Helden 1977, p. 26). If the "systematized" experience of spectacle makers held for Galileo why, then, did it fail for all other opticians and scholars? We submit that it is most likely that Galileo realized that the eyepiece is not for sharpening the image of the objective; rather, it takes part—as an element in a system—in the magnifying process. This stands in contrast to the traditional claim. Galileo, it appears, was a better scientist than the historians of science who have accounted for his extraordinary discovery.

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