The First Telescope

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A typical caption for this iconic illustration reads: “Hans Lipperhey, a spectacle-maker in Middelburg, held a concave lens in front of his eye and a convex one farther away, combining them into the first telescope.” Would the presence of both convex and concave lenses in spectacle shops be sufficient to make a telescope? Why would the craftsman hold lenses in such a way? Perhaps he was simply checking the quality of the surface of the convex lens with a magnifier? That certainly makes more sense. Checking the surface polish during lens fabrication was a routine procedure. Could more details be seen on the surface of the convex lens by placing a concave lens near the eye? No, the convex lens appears diminished in size when viewed through a concave lens. However, a convex lens combined with a convex magnifier gives the Keplerian rather than the Galilean type of telescope invented by Lipperhey. So which type of telescope was made first?

Introduction

The invention of the telescope occurred several centuries after the introduction of spectacle lenses. Why did it take so long to make a telescope from spectacle lenses? The answer can be found in Rolf Willach’s book, a detailed account of the technology and art of lens making from early glasses to the first telescope [1]. However, one seemingly small question has remained unanswered: How did the inventor of the telescope discover his ingenious method of lens improvement, or how did Lipperhey think of the idea of using a diaphragm? This article will delve deeply into the technical aspects of lens making and provide new insights about the invention of the telescope.

Spectacle lens versus telescope objective

In spectacles, a pair of lenses placed a modest distance in front of the eye helps to focus images on the retina. For the average eye, the pupil is dilated to a diameter of only 2 to 3 millimeters in diameter under daylight conditions, so only the small central part of a spectacle lens actively assists direct vision. The remainder of the lens serves chiefly for orientation.

When a lens serves as a telescope objective, it is placed a considerable distance from the eye and its entire surface forms the image of a distant object at its focal plane. An additional lens placed near the eye is required to see an enlarged image.

The lenses in spectacles must be free of small-scale defects such as scratches, bubbles, and prominent striae, at least near the center. Being comparable in size to the daylight opening of the pupil of the eye, any of these defects will have a pronounced effect when viewing through this lens. Such defects can be detected when selecting a suitable piece of glass prior to actually fabricating a lens. Large-scale defects like surface irregularities and variations of the refractive index within the body of the lens are not as critical because only a small part of the lens is in use.

When a spectacle lens serves as a telescope objective, these small defects do not have as pronounced an effect on the quality of the image because they have a relatively small combined area. Conversely, an objective lens is more sensitive to large-scale defects like surface irregularities and internal inhomogeneity. These large-scale defects can seriously degrade the image, but they are not easily detected during lens material selection and may only be seen after the fabrication of the lens is complete. Considering that spectacle lenses were relatively thin, inhomogeneity is less problematic than surface irregularities.

Now we must consider the lens itself. It is a round piece of transparent substance with at least one of its surfaces curved in order to change the convergence of light rays. Glass was the most common substrate for lenses. From early times, lenses had one or both surfaces convex and were used as magnifying and burning glasses, or as a tool to correct the most common vision condition of "old eyes," presbyopia or far-sightedness, the inability to focus on nearby objects.

Let us divide the spectacle lens into zones according to their function. The central zone measuring two to three millimeters in diameter is used for direct vision, while the surrounding zone of at least 10 millimeters diameter is used for peripheral vision. Only the central part of the lens must be of good optical quality. The surrounding outer zone must be transparent, but it does not play a role in correcting vision. However, as a consumer product spectacle lenses must be polished to the edge for cosmetic reasons.

In the case of a telescope objective, the entire surface must be perfectly spherical in order to form a sharp image. Let us also check if the spherical and chromatic aberrations would be affecting the view through a telescope made with spectacle lenses. For most common group of customers aged 40 to 50, [2, 232] the focal length of spectacle lenses was about 300 millimeters. This result comes from averaging the focal lengths of 12 spectacle lenses measured by Willach [1]. With a typical diameter of 30 millimeters for the spectacle lens, spherical aberration is negligible. In fact, a 30 millimeter diameter spherical lens with a focal length of 300 millimeters is diffraction limited for monochromatic light. Chromatic aberration for such a lens would not be as easy to overcome, but we must consider that the first telescopes magnified only 2 to 4 times. At such low magnifications, the spurious color fringes around the image would not be readily visible because they would be near the eye's resolving power in size. Consequently, irregularities in the outer zone of the lens would remain the major limitation.

Lens making techniques and the internal quality of glass in early times were sufficiently advanced to produce spectacle lenses that used only one to two percent of lens surface to help the eye to focus, but a lens of such diminutive size would not be sufficiently large to serve as the objective of a telescope, a device for "making far objects appear close" that requires higher resolving power than the naked eye. To obtain superior resolution, the good part of the lens has to be larger than the opening of the pupil of the human eye. Otherwise the subject would be seen larger, but no details would be added. Furthermore, if the larger outer zone of the lens had an irregular shape and did not bring light rays to a common focus, the resulting image would be blurred unless the peripheral "bad" part of the lens were masked off.

The difference between the size of the useful area of the lens for spectacles and for telescopes was the major factor in keeping the invention of the telescope at bay for several centuries. However, the year 1608 brought a new device to life. Hans Lipperhey, a spectacle-maker from Middelburg, "found a certain art with which one can see all things very far away as if they were nearby“ and demonstrated a working model of the first telescope at the end of September [3,11].

Lens making techniques of the 17th century

Let us focus on the routine work of an ordinary spectacle shop. Work began with the selection of glass. The most common material for lenses was ordinary plate glass made for windows [4] or pieces of Venetian glass made for mirrors. Both surfaces of these materials were polished. Selection was performed by a preliminary visual inspection to find pieces with minimal inclusions and bubbles and good polish, at least in the central part of a future lens. The next step was to determine which side of the glass had better flatness by examining oblique reflections from each surface. The side with less distortion of the reflected image was kept untouched and the opposite side was ground to a nominally spherical curve.

Once pieces of glass were selected they were rounded or shaped to a common size. Typical spectacle frame openings measured about 30 millimeters in diameter.

Rough grinding to impart a convex surface was performed using concave metal tools. This process continued until the ground surface of the lens assumed the opposite form of the tool and became uniform from center to edge.

Fine grinding was performed using the same tool using successively finer abrasives until rough grinding marks and scratches disappeared. At the end of this stage of work the lens surface could produce a reflected image of a bright object and the worker could determine the uniformity of the polished surface by looking at the surface at an oblique angle [5]. The completed finely ground surface usually had a decent spherical shape of opposite sign to the tool that created it. It should be noted that a metal tool wears at a much slower rate than a glass work piece, a vital factor when producing a multitude of lenses with the same curvature.

Once residual particles of abrasive were washed away at the end of fine grinding session, adding a few drops of water rendered the surface of the lens transparent (at least in the central part). The surface was then carefully examined using a magnifier. If scratches were detected, the lens was returned to one of the previous fine grinding stages. It was important to eliminate scratches at this stage so that less time would be consumed during the next step, polishing.

Polishing operations were performed using a different tool. This took the form of a round piece of wood with a flat or slightly curved surface larger in diameter than the lens diameter. Covered with felt or deer skin, it could be affixed to the workbench or rotated on a spindle. During the grinding stages the surface of the lens was gradually made to conform to the hard concave surface of the metal tool, which served as the “master” reference surface, but during the polishing stage the lens surface itself served as the “master” for the pliable surface of the polishing tool.

There are several ways to polish a lens, and not all of them give the same result. Variables include the speed of tool plate (if the tool is rotating) or the speed of lens moving across the tool (if tool is fixed); the relative positions of the lens and the surface of the tool; the number, length, direction, and configuration (straight, circular, oval, etc.) of strokes. All of these factors play a role in determining the quality of a lens.

During the polishing operation, the surface of the lens becomes shiny at the center first and gradually progresses toward the edge because the smaller particles of polishing agent tend to concentrate near the center and larger particles toward the periphery. As a result, the central portion of the lens polishes out first. A spherical shape is imparted to the central zone of the lens, but the outer zone must be polished out by holding the lens holder at an angle relative to the tool, which is not conducive producing a uniformly curved surface. When the entire surface of the lens is polished out, only the central zone will have comparatively good optical quality. The surface of the outer zone will have an irregular shape, but for use as a spectacle lens this result is satisfactory.

If a more steeply curved tool is used to polish out the outer zone, or if the original grinding tool is covered with felt or deerskin for polishing, or if the polishing tool is applied in such a way that the edge of the lens polishes out first, the effect will be to impart an irregular surface at the edge zone early in the polishing operation. This irregular outer zone will spread from the edge towards the center as polishing proceeds, destroying the relatively decent spherical surface that existed when the grinding operations were complete. If the entire surface of the lens has an irregular shape, it will be unsuitable even as a spectacle lens.

Lenses for spectacles were not produced singly but in batches of the same focal length, passing from together from the rough grinding to the fine grinding to the polishing stage. When a batch of similar lenses was completed, the sole remaining operation was to mount them in frames.

Lens conditions and combinations

By the dawn of the 17th century the typical spectacle-making shop produced lenses to correct both myopia ("near-sightedness") and presbyopia ("far-sightedness"). In other words, both convex and concave lenses were made. Two possible combinations of such lenses could be configured to produce a telescope of one of the early forms. Combining a positive (convex) objective lens with a negative (concave) eye lens gives the Galilean form of telescope, while combining a pair of positive lenses gives the Keplerian form.

The historian Albert Van Helden has concluded that the Galilean form had a better chance to be invented first [6, 17]. In my opinion, however, the probability of a telescope of either form was vanishingly small due to the uniformly low quality of spectacle lenses, which only had a decent optical figure over a very small central zone.

The availability of both positive and negative lenses is a necessary, but not a sufficient condition for obtaining a sharp, un-inverted, magnified image. An objective lens of typical spectacle lens quality must either be opaque near the edge (due to incomplete polishing) or its irregular outer zone must be masked off with a diaphragm. When we envision the optical scheme of a telescope, finding the right combination of lenses seems like an almost trivially simple exercise. But why did Lippershey, a mere spectacle-maker, succeed and not the likes of Roger Bacon, Giambattista della Porta or Girolamo Fracastoro, who actually conducted optical experiments?

The Inventor

Experienced lens makers were aware of two possible ways to polish a lens. Evangelista Torricelli, well known during the mid-17th century for his comparatively large lenses of high quality, left us with rare descriptions of early optical fabrication techniques. One of several important remarks contained in a 1643 letter to his friend Raffaello Magiotti concerned polishing: "…never should one polish [a lens] on the same tool plate that has worked it, because it gets polished first at the edge, and then very late in the middle, and they [lenses] do not turn out well" [5, 30]. Torricelli's remarks referred to telescope objective lenses, but they applied to spectacle lenses as well.

Willach's tests [1, 95] of 57 spectacle lenses made between 1500 to 1630 showed that only five examples had a good central zone of 10 millimeters diameter that potentially could surpass the resolution of the naked eye, making them suitable for use as telescope objectives provided that the remainders of their surfaces were covered. The overwhelming majority of lenses was of very poor optical quality and probably made using the polishing techniques described earlier.

Should we regard Lipperhey as an experienced maker of spectacle lenses? He was 38 years old and had been making spectacles for six years prior to the invention of the telescope. No examples of his handiwork survive, so we can only speculate about the quality of his work. But we do know that the performance of his first telescope impressed the burghers of Middelburg, who looked through it. Moreover, within a short time he was able to produce three "improved" instruments suitable for seeing with both eyes, namely binocular telescopes. These facts certainly suggest that he was a maker of lenses of exceptionally high quality. Making a binocular telescope is a demanding task not only for the precision required to align two telescopes in parallel into a single instrument, but also for matching the focal lengths of the lenses used in both telescope tubes to a degree that is far more exacting than would be required for a pair of lenses in single spectacle frame. In a six-month period Lipperhey made at least seven telescopes that are referred to in contemporary documents, the first specimen as a single instrument, followed by three pairs of binoculars. While he was not awarded a patent for his invention, he was handsomely paid for his work. The sum was sufficient for him to buy a large house where he continued to make making spectacles and telescopes.

Many readers may consider the details about the grinding, polishing, and testing of lenses as rather boring. However, the details of the routine work of a spectacle-maker's shop – a thorough understanding of the steps involved in making a lens -- contains the key to answering a very important question: How did the inventor of the first telescope arrive at the idea of covering the part of the lens that had an irregular shape and gave distorted images?

The act of invention

It is probable that Lipperhey's invention of the telescope stems from a chance occurrence when he was performing routine tests on batches of lenses, either the end of the fine grinding stage or at the beginning of the polishing stage. At these times the central part of the lenses becomes transparent, but their edges remain opaque. This is the only condition in which a spectacle lens is capable of forming an image that is not seriously degraded by irregularity of the outer zone. Checking the surface of a lens for imperfections with a magnifier by looking at and through it against the uniform background illumination of the sky was probably the fortuitous situation when Lippershey was able to discern the magnified image of distant objects like the rooftops of the houses across the street.

The only problem with this combination of a pair of positive lenses is the inverted image it produces. One would certainly hesitate to demonstrate an instrument that showed everything upside down, let alone apply for a patent! But Lipperhey had in his shop both convex and concave lenses. Trying to cure the problem of inverted images, he would have replaced the magnifier with a concave lens and combined it with the same unfinished convex lens. By moving the convex lens farther from the concave lens he obtained an uninverted magnified image of distant objects. According to Albert van Helden, the telescopic effect is very easy to discern with the Galilean lens configuration [6, 18], and I certainly agree with the author in this instance.

It seems probable that Lippershey knew of both the Keplerian and the Galilean form of telescope. He stumbled upon the Keplerian form while performing a routine inspection of spectacle lenses with a magnifier, then he deliberately devised the Galilean form that employs a negative concave eye lens when he attempted to solve the problem of the inverted image. We can regard the Keplerian form as a discovery, while the Galilean form deserves the status of an invention. Although he was not a scientist, Lipperhey deserves the lion's share of the credit for the novel instrument that he invented by chance. He left the astronomical discoveries for others. He may not have even looked at celestial objects through his telescope – what would be the reason? There were so many interesting earthly subjects for the magic of his new instrument.

Since spectacles lenses had to be finished with polishing to their very edge, Lipperhey would have determined that masking the outer part of the lens gives virtually the same result as leaving an opaque unpolished edge zone. This was the birth of the diaphragm or aperture mask, an elegantly simple way to prevent the optically imperfect outer part of the lens from destroying the sharp image created by the good central part. This idea was soon repeated by others.

Because the telescope was a practical invention, not a theoretical one, Lipperhey was first simply because he was using better polishing techniques than his contemporaries. Compared to optical scholars who had a "lack of attention to lenses" [7], Lipperhey was obliged to pay very close attention to the art that was the source of his livelihood, and he had to test a host of lenses. The State General not only accepted his creation but soon asked him to construct a more complicated device - the binocular telescope.

Conclusion

The invention of the telescope at the beginning of 17th century became possible only when the central part alone of a spectacle lens was used to form the image. Full-aperture lenses performed adequately for spectacles, but they were not suitable for telescope objectives. This requirement makes it clear that the stories about children playing with lenses being responsible for the invention of the telescope or Girolamo Sirtory's tale [3, 19] of the stranger who visited the shop in Middelburg, tested lenses in front of their maker, who then got the idea of constructing a telescope, are all sheer fantasy.

The leap from the low-power terrestrial telescope to the first astronomical instruments made by Galileo required using a diaphragm as well. That simple refinement remained a key optical aspect of the telescope for over a century.

Author's moment of revelation

I make my living making modern telescopes. Antique telescopes are my hobby, an escape into the past from the everyday routine of the opto-mechanical workshop. My thoughts first turned to the invention of the telescope in September 2008 during a visit to Middelburg, where I attended a conference on the occasion of the 400th anniversary of the invention of the telescope along with other members of the Antique Telescope Society. Even after listening to several interesting lectures at that conference, notably those by Rolf Willach, Giuseppe Molesini, Marvin Bolt, Sven Dupre and studying the subject further, I did not arrive at any original insights.

The breakthrough came two years later after a friend in France asked me to solve a problem with the 110-millimeter aperture air-spaced doublet objective of his century and a half-old refractor made by Secretan. The achromatic objective did not give sharp images. Cursory tests revealed poor color correction and a very objectionable amount of spherical aberration. My first thought was that the objective had been incorrectly assembled, but that was not the case. In fact, the lens elements of the objective had been made very accurately, but it had been improperly designed.

Sometimes less effort is required to simply make a new lens from scratch than to repair a defective one. My friend simply wanted to observe with the telescope, so I suggested that I simply make a new objective lens to replace the defective original. Glass blanks were purchased and rudimentary tooling was made. I am not an optician, but with the help of professionals the replacement objective was successfully completed. I decided to make several additional objectives from the remaining glass.

I was working on them for a couple of months after normal working hours and on weekends, performing all the stages of lens making. Once, when I was examining the surface of a lens element during the final stage of fine grinding using a magnifying glass in an attempt to determine if any scratches remained near the edge, it dawned on me that an unpolished edge acts like a diaphragm -- an opaque outer zone surrounding a transparent central zone. This is the lens condition in which the irregularities of figure in the outer zone do not detract from the quality of the image. I said to myself this was probably the same circumstance that Lippershey encountered when he was testing his lenses and observed the telescopic effect.

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1 Rolf Willach, "The long route to the invention of the telescope"

2 Vincent Ilardi, "Renaissance vision from spectacles to telescopes"

3 Huib J. Zuidervaart, "The 'true inventor' of the telescope. A survey of 400 years of debate" in the book "The origins of the telescope" (2010)

4 Rolf Willach, "The development of lens grinding and polishing techniques in the first half of the 17-th century" in "Bulletin of the Scientific Instrument Society, #68 (2001)

5 Giuseppe Molesini, "Telescope lens-making in the 17th century" in OPN Optics & Photonics News,l 2010

6 Albert Van Helden, "The invention of the telescope" (2008)

7 Vasco Ronchi, "The Nature of Light: A Historical Survey".