

PERFECTING 'A SHARPER IMAGE': TELESCOPE-MAKING AND THE DISSEMINATION OF TECHNICAL KNOWLEDGE, 1700-1820

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Abstract: Telescopes, reflecting telescopes in particular, underwent considerable development during the eighteenth century. Two classes of telescope maker, the for-profit artisan and the amateur 'gentleman-philosopher,' learned techniques of optical fabrication and testing and produced usable astronomical instruments. One means of disseminating technical knowledge was via the book. The year 1738 saw the publication of a highly-influential book, Robert Smith's *A Compleat System of Opticks*, a work that included detailed information on telescope-making. It was this book that helped spark the astronomical career of William Herschel, and with Smith's information Herschel produced large reflecting telescopes of exquisite quality. However, artisan-opticians, even the renowned James Short, appear to have cut corners on a portion of their production, thus permitting the sale of some instruments of inferior quality. The reasons for this were clearly economical in nature: artisans depending on telescope sales to earn a living simply could not afford the time required for perfection. The mere presence of written works disseminating technical knowledge did not ensure that such knowledge was universally adopted.

Keywords: telescope, telescope-making, economics, technology transfer

1 INTRODUCTION

The telescope was one of the most crucial developments in the history of scientific instruments. For the first time, one could see with one's own eye objects that would otherwise have been mere points of light in the sky, or misty specks on the sea's horizon. The telescope, along with the microscope, was one of the keys that propelled European civilization into the modern world. Science, navigation, exploration, war, and even recreation all benefited from the invention of the telescope. However, early telescopes were extremely crude devices and relatively little information regarding their manufacture was available at the time. Galileo Galilei, Johannes Kepler, René Descartes, Isaac Newton, and other mathematical-philosophers of the period wrote short treatises on telescopes, in addition to more extensive works on optics generally, but had relatively little to say concerning details of construction. There were several key steps involved in the perfection of the telescope and the transmission of knowledge concerning optical fabrication and testing that occurred between about 1700 and 1820. While the fundamental processes of making telescope lenses and mirrors changed little, drastic changes occurred in the materials used, and most especially, the methods of testing optics. Assorted experiments and experiences in telescope-making resulted in a considerable body of knowledge, but the successful transmission of such knowledge remained problematic. By the mid- to late-nineteenth century, the results of all these developments were commercially-made telescopes of great quality, but equally great expense.

The vast majority of telescope-owners were of the educated, genteel elite. The average cost of telescopes during this period was tremendous, far beyond the means of most. Until the mid-twentieth century much of the expense of telescopes derived from fabrication methods. Mass production was a thing of the distant future in eighteenth century Europe, and telescopes, like everything else, were individually hand-made. An option for those with some talent was to make their own telescope.

However, construction of such a precise instrument required a high degree of technical knowledge and ability. Transmission of technical knowledge was central to the development of the reflecting telescope. A well-known text of the period, Robert Smith's *A Compleat System of Opticks* (1738), provided the first truly exhaustive description of the telescope-makers' art. How it influenced the work of two important and near-contemporary eighteenth-century telescope makers, James Short and William Herschel, illustrates the problems with the transmission of important technical knowledge concerning astronomical instruments. Smith's work was essentially a conduit of knowledge, rather than a seminal foundation of knowledge, and some telescope-makers, such as Short, appeared to dismiss some of the valuable information it provided for reasons beyond the purely technical.

2 TELESCOPE-MAKERS OF THE EIGHTEENTH CENTURY

Telescope making to about 1860 was dominated by two classes of telescope-maker: the professional artisan (e.g. see Figure 1) and the 'gentleman-scientist'.

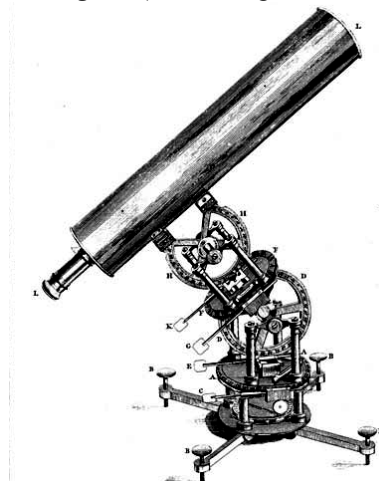


Figure 1: Example of a reflecting telescope by professional telescope-maker James Short (adapted from Wikimedia Commons).



Figure 2: Robert Smith, 1689–1768. Portrait by John Vanderbark, painted in 1730 (courtesy: Wikipedia).

The professional artisans—men such as James Short 1710–1768), John Dollond (1706–1761) and Peter Dollond (1731–1821)—were members of a larger class of scientific and mathematical instrument-makers who were in business to sell their wares. In a world where patent law was difficult to enforce, they tended to keep manufacturing methods a close secret, and relatively little can be learned from their surviving records (if any) concerning how they produced their instruments. European telescope-makers prior to 1900 were very much within the traditional European guild system, as were many other crafts, such as printing and dyeing. The influence of guild secrecy amongst professional European telescope and ‘philosophical instrument’ manufacturers was felt into the early twentieth century, even after the guilds had ceased to exist as such. The art and science of optical fabrication were passed down from master to apprentice, and there were neither formal training nor textbooks as such on the subject until the twentieth century. On the other hand, gentleman-scientists, or more correctly, ‘gentleman-philosophers,’ were not bound by secrecy as were the artisans; it was in fact their duty to expand the knowledge of all concerning

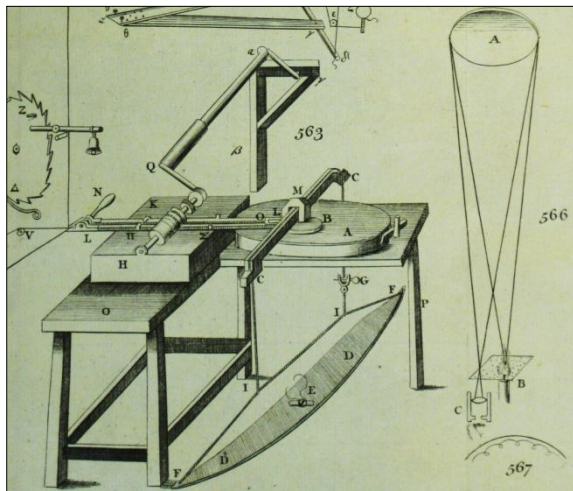


Figure 3: Illustration from Smith's *A Compleat System of Opticks* (1738). Figure 566 on the right is the original visual depiction of Hadley's mirror test. B, the perforated metal screen, and C, the observation lens, were both placed at the center of curvature of A, the mirror being tested. Figure 563 in the center is an example of a proposed treadle-operated lens grinding machine.

science and scientific instruments. Some gentleman-philosophers were professionals (university and government employees) while others were amateurs (wealthy individuals with philosophical/scientific aspirations). It is from this latter group that most can be learned of optical production methods between 1700 and 1820. It was also the gentleman-philosopher who was the key in making these methods known to a wider audience in their own day.

A complete, detailed history of the development of telescope technology is not the purpose here, nor is the uses to which telescopes were put. These subjects have already been covered elsewhere, particularly by Henry King in *The History of the Telescope* (1955). However, understanding the technical details of telescope-making between 1700 and 1820 and how information was communicated, altered, and re-transmitted, is of considerable importance in illustrating a particular facet of scientific-technical knowledge and communication within the broader context of eighteenth century European science and technology.

Scientific instrument-makers from the seventeenth to nineteenth centuries were a diverse group and produced diverse products, including telescopes. London was the center of both the scientific instrument and telescope-making world during much of the eighteenth and nineteenth centuries. British census records through 1851 do not indicate exactly how many ‘opticians’ and ‘philosophical instrument makers’ actually made telescopes, but surviving examples of telescopes and advertising suggest that at any one time there might have been several dozen instrument-makers who produced telescopes in England, Scotland and Ireland, most concentrated in London (see Burnett and Morrison-Low, 1989; Clarke, et al., 1989; and Clifton, 1995). The actual guilds to which telescope-makers and instrument-makers belonged were diverse, and sometimes unexpected. Robert Banks (or Banks, who worked in London between 1796 and 1831), a known maker of both telescopes and microscopes, was a member of the Joiners Guild, and Francis Hauksbee (d. 1765) belonged to the Drapers Guild (Clifton, 1995: 16, 128). In truth, the whole subject of scientific instrument-makers, as opposed to the instruments they made, is a remarkably little-studied field in the history of science and technology, and is limited to a famous few, such as Jesse Ramsden. As a result, most of what is known of their work is limited to examination of extant instruments, and these have little to say about how they were made.

3 SMITH'S A COMPLEAT SYSTEM OF OPTICKS

Although some written accounts of the details of lens-making and mirror-making prior to the eighteenth century were made known publicly, these were very few and, in many cases, intentionally vague. In his *Opticks*, Isaac Newton (1642–1727) described some details of his own methods for fabricating his reflecting telescope; his techniques seem basically similar to those of other telescope-makers of his era, but even he gave few details (see Newton, 1721: 91–95). As stated previously, prior to effective enforcement of patent law, fabrication methods were a closely-guarded secret among members of the var-

ious craft guilds, a state of affairs that existed well into the nineteenth century. As a result, little is known, either then or now, of the details of the early lens- and mirror-making craft. Among the first widely-disseminated works on optical fabrication, as opposed to theory, was Robert Smith's *A Compleat System of Opticks* (1738). Smith (Figure 2) was a well-known natural philosopher at the time, serving as Plumian Professor of Astronomy and Experimental Philosophy at Cambridge from 1716 to 1760. Besides contributing his own theoretical and mathematical knowledge, Smith compiled material on telescope-making from a number of well-known individuals, including the Dutch natural philosopher and astronomer Christian Huygens and the British astronomers Samuel Molyneux and John Hadley, among others, and it was Smith's book that later acted as a guide for the noted astronomer and telescope-maker William Herschel.

A Compleat System of Opticks was quite typical of any number of philosophical-technical works of the period, such as Diderot's *Encyclopédie* (1751-1772), or the earlier *Cyclopædia, or an Universal Dictionary of Arts and Sciences* (1728) of Ephraim Chambers. Books such as these provided a wealth of information to the educated layman on a host of technical subjects. Smith sought to put together a work that would expand on all previous ones, and would be useful to a wide range of readers. The 'popular' introductory section was non-mathematical and was "... for the use of those who would know something of Opticks, but want the preparatory learning that is necessary for a thorough acquaintance with that Science." (Smith, 1738: i). More importantly, Smith intended the introduction to be sound enough to permit readers to understand the later volumes in his work, "... especially if their heads be a little turned towards mechanical matters." (ibid.).

It is worth exploring the details of Smith's "Book III", as it describes the fundamental techniques involved in grinding and polishing lenses and mirrors (e.g. see Figure 3). Smith (1738: 281) acquired much of his knowledge of practical optics and lens production through his friend Samuel Molyneux (1689-1728). Molyneux served as Lord Commissioner of the British Admiralty and as such was no doubt interested, both personally and professionally, in passing on everything learned concerning astronomical and navigational instrumentation. Smith himself apparently knew little concerning the actual techniques of fabricating lenses and mirrors; what he presents in Book III is largely the work of others. As a result of Smith's unfamiliarity with fabricating technique, it is a somewhat confusing account at times, demonstrating some of the problems with communicating the technical details of scientific instruments and technology, even among 'experts'.

The section on lens production is based almost entirely on the work of Christiaan Huygens (Figure 4), which Smith (1738: 281) considered "... the best of any yet extant." Huygens produced a number of the largest and best refracting telescopes made in the late seventeenth century and used them to make various important discoveries (including the nature of Saturn's rings), and he worked out a number of fabrication techniques for lenses (King, 1955: 51).

The objective lenses of all refracting telescopes up to about 1750 were made from a single piece of ordinary glass, referred to as 'crown-glass'. As a result, such simple lenses suffered from a number of problems, primarily spherical aberration and chromatic aberration, cured only by making lenses of relatively small diameter (a few inches) and of very long focal-length (over a hundred feet in some cases). Smith's description of Huygens' methods take the reader step-by-step through all aspects of lens production, including how to make the brass grinding tool, how to choose quality glass, the rough and fine grinding process, and polishing (Smith, 1738: 282-301). Although Huygens' methods would be familiar to telescope-makers today, there are some differences; for instance, the concave grinding and polishing tool (described by Smith as a 'plate' or 'dish') is made considerably larger in diameter than the finished lens, rather than the same size. Polishing appeared to be the problematic aspect of lens-making for Smith and Molyneux, as at least three different methods, or variations of methods, are described. An aspect of telescope-making that was, and continues to be, of



Figure 4: Christiaan Huygens, 1629-1695 (courtesy: Wikipedia).

crucial importance, is the quality of the glass required for lenses; this proved to be a major stumbling block to the improvement of refracting telescopes for many years (see Smith, 1738: 287-288). Grinding the curved surface of lenses then as now involved the use of an abrasive slurry, usually consisting of powdered emery (natural corundum, an aluminum oxide) and water. Once the curve had been generated by grinding with a coarse grit, finer and finer grades of emery were used to remove the large pits in the glass created by coarser stages of grinding.¹

Polishing the lens to remove all traces of grinding, thus making the lens completely transparent and free of pits and scratches, was generally done with an extremely fine abrasive such as jeweler's rouge (ferric oxide, Fe_2O_3), or 'tripoly' (decomposed siliceous limestone), on a yielding surface. Huygens is quoted by Smith as using tripoly directly on a copper tool,



Figure 5: John Hadley, 1682–1744 (after Andrews, 1993: 28).

while others used linen, leather, paper, or other soft surfaces. Smith must have misinterpreted Huygens, since polishing directly on the metal tool would have left numerous fine scratches. Smith's narrative of the process admits some confusion, by use of the phrase "... if I understand Mr. Huygens right [the linen cloth is removed after using it to wipe the lens with tripoli]." (Smith, 1738: 293-294). Smith's confusion helps demonstrate how little was generally known about the craft of lens-making at the time. The majority of grinding work was done by hand, but polishing was considered by most workers to require considerable pressure, and so machines of one kind or another were used (Smith, 1738: 297-301). The last stage of lens production involved *centering* the

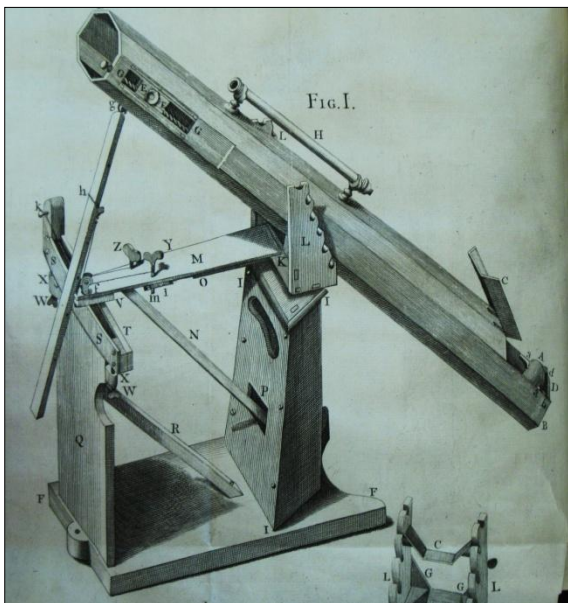


Figure 6: Hadley's 6.2-inch aperture Newtonian telescope. Though his was a highly efficient design for the dedicated astronomer, Hadley's arrangements lacked the fine materials and aesthetics of Gregorian telescopes (after Hadley, 1723: Plate 2).

lens; that is, making sure both faces of the lens had coinciding foci along the same optical axis. The centering process would often result in significant portions of the lens being cut away and discarded (Smith, 1738: 312-317). This last step seems to be the end of the process and nothing is really said about *testing* the final lens beyond the assessment involved in the centering process.

Smith then goes on to describe the method for making 'specula', or telescope mirrors, as described by Samuel Molyneux and John Hadley. It is this section of Smith's book that gave William Herschel, and no doubt others, important clues to many details of telescope-making. Reflecting telescopes had been theorized about since the early seventeenth century, but it was Isaac Newton who produced the first working models of such telescopes in 1668-1670 using a mirror made of 'speculum metal', an alloy of copper and tin. After the experiments of Newton and a few others, little more was done concerning the fabrication of reflecting telescopes until John Hadley applied his knowledge and abilities to the problem.

Hadley (Figure 5), a mathematician and instrument-maker from Essex, was notable for producing the first 'large' Newtonian telescope, large being a comparative term as Newton's original had an aperture of less than two inches while Hadley's was a 6-inch. Hadley's reflecting telescope of 1719-1720 (see Figure 6) caused a sensation. The telescope worked well, as can be attested by the drawing of Saturn appearing with Hadley's description of his telescope in the *Philosophical Transactions* (Hadley, 1723: Plate 376; cf. Smith, 1738: 301-312).² Hadley's letter had little to say concerning how he made either the optics or mechanical parts of his telescope; fortunately, later correspondence with Smith provided many answers. *A Compleat System of Opticks* provides details of making the speculum metal disc from which the mirror was made, through rough grinding, fine grinding, and polishing (Smith, 1738: 304-305). The fabrication methods used were very similar to those for lenses at the time, aside from the different material used for the mirror itself (Smith, 1738: 306). The correct proportion of metals used was a matter of considerable argument and experimentation well into the nineteenth century. Hadley, with the assistance of Bradley, tried one hundred and fifty different formulae for speculum metal before they came across the one that worked best, a combination of two alloys, the first of three parts of copper and one part and a quarter of tin, the second of six parts of brass and one part of tin. Telescope-makers continued to fiddle with the details of these proportions, but speculum metal was essentially the same copper-tin/brass alloy.

Of particular note, however, is that Hadley not only described his method of *making* mirrors, but also of *testing* them. Optical theory, then as now, shows that in order to form a good image of an object at infinity the cross-section of the surface of a reflecting telescope's mirror must be a paraboloid. This is a very difficult surface to produce for a number of reasons. First, the method of making mirrors is like that of making lenses: two discs are ground against one another, one convex the other concave. The natural shape produced by the grinding process

(and later, the polishing) is a sphere. It requires somewhat different motions to produce an aspherical surface on either a lens or mirror and the special techniques for this are quite demanding. A second reason for difficulty is that the difference between the required spherical and paraboloidal surfaces of a telescope's mirror is very tiny, of the order of a few hundred nanometers.³ As a result, the difference between the two surfaces is impossible to detect by any normal means. Indeed, the testing of telescope optics was one of the major stumbling blocks to advances in telescope technology until the mid-nineteenth century. Hadley's method (see Figures 3 and 7), as described in *The Compleat System of Opticks*, continued to be used into the nineteenth century. Hadley understood well the basic geometry of optics and how light-rays behaved after being reflected from a concave mirror (Smith, 1738: 6-27; Willach, 2001: 3-18). The correct paraboloidal surface is slightly deeper in the middle than a spherical mirror of the same focal-length. Hadley's test took advantage of his theoretical knowledge and he developed a simple, graphical and qualitative test for different surfaces (Smith, 1738: 309-312).

Hadley's test was quite simple. Light from a candle was allowed to shine through a very small hole, commonly the size of a pin-point, in an opaque screen. The light would then reflect off the surface of the polished mirror, and the observer then examined the reflected image of the pin-hole by using a magnifying lens. Both the pinhole/light-source and the lens were located at the center of curvature of the mirror (twice the focal length), and the pin-hole served as an artificial star. Hadley clearly understood the test process in the same way as modern opticians: light-rays from the object reflect off the mirror's surface and are brought to a single focal point, or not, depending on any flaws (regions of the mirror that were either higher or lower than theoretically predicted) in the mirror's surface that might be present. The appearance of the artificial star's image at the focus as seen magnified by a lens could thus be used to interpret the mirror surface (see Figure 8):

If the light, just before it comes to a point, have a brighter circle round the circumference [edge], and a greater darkness near the center, than after it has crossed and is parting again; the surface is more curve[d] towards the circumference and flatter about the center, like that of a prolate spheroid round the extremities of its axis; and the ill effects of this figure will be more sensible when it comes to be used in the telescope. But if the light appears more hazy and undefined near the edges, and brighter in the middle before its meeting than afterwards, the metal is then more curve[d] at its center and less towards the circumference; and if it be in a proper degree, may probably come near the true parabolick [sic] figure. *But the skill to judge well of this must be acquired by observation.* (Smith, 1738: 310; my italics).

Note that a spherical mirror tested at the center of curvature gives a perfectly sharp image at the focus and symmetrical intra- and extra-focal images. The importance of such a test as Hadley's cannot be over-emphasized; this is *the* most critical portion of the entire telescope-manufacturing process. Without it, fabrication of the telescope speculum was more guesswork than anything else, and resulting telescope

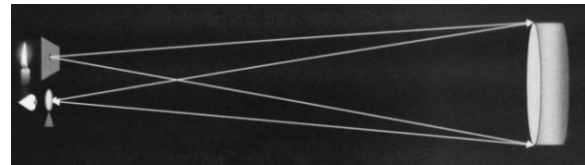


Figure 7: Hadley's arrangement for testing mirrors at the center of curvature (illustration by G. Cameron; cf. Figure 3).

performance could be mediocre at best. The problem with Hadley's test, as he clearly admitted, was that it is *qualitative*, rather than *quantitative*: the determination of whether the surface under examination was a *true* paraboloid or not was a matter of judgement requiring some considerable practice. As will be seen, modern tests of eighteenth century telescopes indicate that even some of the best opticians of the day produced mirrors of somewhat variable quality.

4 AN ARTISAN TELESCOPE-MAKER: JAMES SHORT

A few opticians in London made small reflecting telescopes after Hadley, but relatively little is known of these (see King, 1955: 84). It was James Short, a Scot who later moved to the center of the scientific instruments trade in London, who would dominate the manufacture of reflecting telescopes in Britain during much of the eighteenth century. Short was university educated and became interested in telescopes in the 1730s. He met mathematician Colin Maclaurin (1698–1746) at the University of Edinburgh during one of the latter's popular lectures on astronomy and the two worked together for a time, Short being allowed use of a room at the University for experiments in telescope-making (King, 1955: 84; Maclaurin, 2000). Short produced a few Newtonian telescopes, but the vast majority of instruments he made were Gregorian reflectors. Short had a long career as a telescope-maker, and a reputation as one of the best in his day (Willach, 2001: 16). Prices are known for his telescopes, and these ranged from 3 guineas for a diminutive "3-inch focus" telescope of 12-power magnification, to a "144-inch focus", of 24-inch aperture and 1200-power, for 800 guineas (see Table 1). The vast majority of telescopes produced by Short were in the smaller 7-inch to 18-inch focal length range (and just 2-inches to 3.5-inches in aperture). Most of Short's telescopes that were sold were quite small: of 1,342 made, only

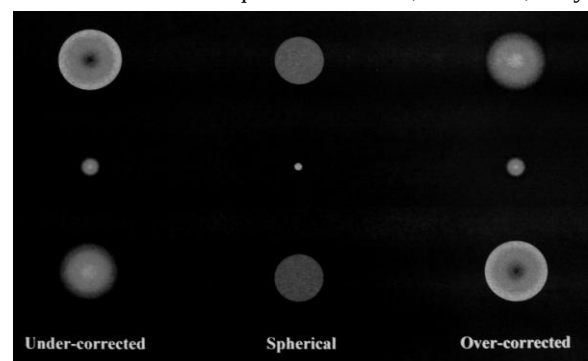


Figure 8: Hadley's testing method – images of artificial stars as seen with a magnifying lens at the center of curvature of a mirror. In each case, the upper image is what is observed just inside the focus, the middle image is at focus, and the lower is just outside the focus (illustration by G. Cameron).

Table 1: Catalogue prices for James Short telescopes ca.1760 (partially based on table reproduced in Clarke, Morrison-Low, and Simpson, 1989: 2).*

No.	Aperture (mm)	Focal Length of Primary (mm)	Overall FL (mm)	Magnifying Powers	Price (guineas)	Price (US\$)
1	25	76	457	12 (terrestrial use only)	3	600
2	33	115	686	25 (")	4	800
3	48	177	1,067	40 (")	6	1,200
4	63	241	1,448	40 and 60	8	1,600
5	75	304	1,829	55 and 85	10	2,000
6	75	304	1,829	35, 55, 85, and 110	14	2,800
7	96	457	2,743	55, 95, 130, and 200	20	4,000
8	111	615	3,657	90, 150, 230, and 300	35	7,000
9	165	914	5,846	100, 200, 300, and 400	75	15,000
10	235	1,219	7,315	120, 260, 380, and 500	100	20,000
11	304	1,829	10,973	200, 400, 600, and 800	300	60,000
12	615	3,657	21,946	300, 600, 900, and 1200	800	160,000

* A full list of prices (date unknown, but likely c.1760) includes all known models of Short telescopes. Telescopes were listed by 'Number' and by the focal length, as was typical for all telescopes of the seventeenth and eighteenth centuries. Short and other makers of Gregorian telescopes gauged 'focal length' by that of the primary mirror rather than the overall focal length of the telescope. Secondary mirrors of Gregorian and Cassegrain telescopes magnify the image several times; thus the 'effective focal length' of the complete telescope would be much longer. My own analysis of data from some of Short's telescopes (described by Willach) gives a secondary mirror magnification of about 6× on average. Table 1 is a combination of data from Short's original price list cited above (columns 1, 3, 5, and 6), combined with the aperture, overall focal length, and approximate price in U. S. Dollars as of 2011 calculated by myself (columns 2, 4, & 7).

about 380 were of an aperture greater than 3 inches, the 2.5-inch size being most popular. Such small telescopes would have been of limited astronomical use and were equivalent in light-gathering power to refracting telescopes of half their aperture.⁴ This, plus what little anecdotal information there is on Short's customers, would suggest that the vast majority of people buying these smaller telescopes were mostly interested in acquiring something they could use for casual viewing of terrestrial objects, and perhaps a glimpse of the Moon.

A modern analysis by Willach (2000: 8-14) of several James Short telescope mirrors shows that, while a few primary mirrors (about 20%) were considered good even by modern standards, the majority show considerable under-correction; many are in fact nearly spherical in cross-section. The small secondary mirrors of Short's telescopes are likewise far from the theoretical shape required. Views through the Short's under-corrected telescopes have a somewhat soft appearance as a result of spherical aberration when viewing various objects. Tests were performed on 16 different Short telescope mirrors ranging in size from 1.6 to 9.25 inches in aperture (40mm to 235mm). Though Willach considered Short's telescope mirrors to be fairly good, some of them would have suffered well over 1-wave of spherical aberration, which is about four times the amount that is generally found acceptable today.

An obvious problem in evaluating the optical quality of Short's telescopes, and indeed any speculum metal reflecting telescope, is the likelihood that the mirrors have been re-polished many times. As a result, knowing which optical surface was produced by a particular hand, Short's or someone else's, is problematic. Willach has argued that it is unlikely that the mirrors that he tested had been re-polished by their owners as the surfaces show a symmetrical figure without zonal errors or astigmatism that might result from buffing with a cloth (Willach, 2001: 16-18). This leaves the possibility that the Short mirrors were re-polished by a skilled optician, an idea that

Willach also dismisses due to the nature of the various mirrors' optical figure.⁵ This analysis, along with the fact that the speculum alloy used by Short appears fairly resistant to tarnish, strongly points to the sixteen telescopes tested having optics figured by Short, not by another optician or opticians.

While one can argue with Willach concerning whether the Short telescopes he has examined were not at some point repolished and refigured by another optician, *if* the mirror surfaces *were in fact* produced by Short, would not an optician of his skill have noticed the considerable differences in image quality between his best and worst instruments? Undoubtedly, he *would* have noticed and attempted to correct the defects. The difference in the appearance of objects as seen through a telescope with nearly perfect optics versus one with 1-wave of spherical aberration is readily apparent, even at low magnification. We are left with two possible conclusions. First, that the poorer-quality Short telescope mirrors were re-polished and refigured by someone else. Second, that Short left them as they were: in an imperfect state. There is thus an obvious problem here. The best telescope-maker of the mid-eighteenth century made and sold a fair number of inferior-quality telescopes.

Short was highly secretive about his manufacturing methods, so the tests he used remain a mystery. As Smith had related in *The Compleat System of Opticks*, the Hadley test depended greatly on the skill of the person doing the testing. It is likely that Short used Hadley's 'in-shop' method or some variation of it. Although Short was one of the most celebrated telescope-makers of the mid-eighteenth century, many of his instruments were far from perfect, even by his own standards (see Table 2). Therefore, the shock felt by those used to Short's telescopes when they observed with the vastly-superior telescopes made by William Herschel just a few years after Short's death can be understood.

Table 2: Evaluation of the optical quality of sixteen James Short telescopes based on data from R. Willach.*

Short Telescope Number	Aperture (mm)	Radius of curvature (mm)	Approximate surface error	Comments
1734 7.14	40	202	4.43λ	Basically a spherical mirror with slightly turned-down edges.
1735 10.45	47	282	1.73λ	Corrected to about 50% required of a parabola.
1740 29/269=7	47.7	346	0.76 λ	Smooth curve, good approximation of parabola.
1742 15/322=12	72	636	1.33 λ	Spherical with outer 30% over-corrected.
1741 4/297=24	120	1240	0.51λ	Approximately parabolic in outer 50%; spherical center.
1744 44/390=18	97	900	0.34λ	A good mirror.
73/556=18	97	883	0.46λ	A good mirror.
114/803=18	97	816	0.56λ	Approximately parabolic in outer 50%; outer zone over-corrected.
138/878=12	75	630	1.44λ	Spherical with outer 30% over-corrected.
244/1063=9.6	63	488	0.44λ	A good mirror.
189/1151=18	97	907	0.17λ	An excellent mirror.
42/1195=24	112	1228	0.97λ	Approximately parabolic in outer 50%; spherical center.
44/1198=24	111	1225	0.06λ	Superb—by far the best.
214/1235=18	96	895	1.35λ	Spherical with outer 30% over-corrected.
252/1313=18	97	881	1.65λ	Spherical with outer 30% over-corrected.
6/1364=49	235	2500	1.38λ	Spherical with outer 30% over-corrected.
Herschel's 7-foot telescope	170	4267	0.15λ	Would have been excellent even if left spherical.

* The table above is based on the data published by Rolf Willach (2001) along with my interpretation of Willach's test results. In calculating the approximate surface errors of the mirrors, the following equation was used:

$$\Delta z = [R - \sqrt{R^2 - h^2}] - h^2/2R$$

An error of 0.25λ (Rayleigh's limit) has been utilized for many years as an indication of a reasonably good mirror, though more modern testing and fabrication methods have superseded it among professional opticians. Still, it gives a reasonable indication of overall optical quality. For comparison, results for a William Herschel 6.7-inch, 7-foot focus Newtonian were also calculated; note that, even if left spherical, the long-focus Newtonian is superior to all but one Short Gregorian telescope.

5 A 'GENTLEMAN-PHILOSOPHER' TELESCOPE-MAKER: WILLIAM HERSCHEL

In terms of both size and quality, reflecting telescopes of the late-eighteenth and early-nineteenth centuries reached their zenith with those of William Herschel (1738–1822). Herschel (Figure 9), originally a musician by profession, took up astronomy as a hobby after his move to England from Hanover, though he had been exposed to mathematics, astronomy and natural philosophy since boyhood (Hoskin, 2011: 11-30; Sidgwick, 1953: 17-20). Herschel had long maintained an interest in the sky, but this increased in the 1770s. His diary entries during 1773 repeatedly mention not only purchases of books on astronomy, but also the hiring of several small reflecting telescopes. Herschel also records the purchase of object glasses, tubes, and eyepieces for small refracting telescopes, and "... tools for making a reflector. Had a metal [mirror blank] cast." (Sidgwick, 1953: 47-55). Herschel bought several telescopes, the smallest being of 4-foot focus, magnifying 40-times, and longest of 30-foot focus, likely simple non-achromatic refractors. William's sister, Caroline (1750–1848), recalled that when they passed through London on one journey in 1773 virtually the only shops they stopped at were those of opticians. Among the books that William Herschel read was Smith's *Compleat System of Opticks* (Hoskin, 2011: 13, 28-30; Lubbock, 1933: 65-66; Sidgwick, 1953: 49).

Herschel became greatly interested in the relative compactness of the various types of reflecting tele-

scopes, both Gregorians and Newtonians. But, as with many future amateur astronomers, he found the cost of commercially-available telescopes to be prohibitive, so he then decided to attempt making his own "... with the assistance of Dr. Smith's popular treatise on Optics." (Sidgwick, 1953: 55-56). One of Herschel's neighbors in Bath was an amateur telescope-maker who had given up the hobby, so William



Figure 9: Sir William Herschel, 1738–1822 (after Holden, 1881).

quickly purchased all of his tools and unfinished mirrors. The purchase of additional speculum metal discs for more telescopes soon followed, and Herschel became totally immersed in telescope-making in his spare time. Herschel quickly produced a Gregorian telescope by October, 1773 and a 4.5-inch Newtonian the next year (Gargano, 2012: 31; Hoskin, 2011: 30-32). By 1791, Herschel claimed to have produced 200 mirrors of 7-foot focus (6 to 6.7-inch aperture), 150 of 10-foot focus (8 to 10-inch aperture), and 80 of 20-foot focus (12 to 18-inch aperture).

Most of the telescopes Herschel made were of the Newtonian type, but, in an effort to reduce light-loss from multiple reflections, the larger sizes were of a single-mirror design now referred to as a 'Herschelian' (Sidgwick, 1953: 56-61). The large number of mirrors made for use by Herschel likely included numerous duplicates and failed experiments. Speculum metal is a difficult material to make and work with. There are many instances of speculum discs that shattered or became warped, possibly due to poor annealing. Besides this, makers of speculum-metal reflecting telescopes generally made at least a pair of mirrors for each telescope so that as a mirror became tarnished by exposure to the air, its 'twin' could be installed in the telescope while the original mirror was being repolished.

Herschel seems to have preferred testing his telescopes on the stars, rather than in the shop; however, the test he used was likely a variation of Hadley's method, substituting an actual star for the illuminated pin-hole. The crucial modification Herschel made to Hadley's test was that, when observing a star at infinity, the correct parabolic 'figure' of the mirror would produce the *same symmetrical series of intra- and extra-focal images* as produced by a spherical mirror tested at its center of curvature. Thus for Herschel, there would be no question of judgment as to whether the figure of the mirror was elliptical, parabolic, or some other figure as in Hadley's test; if one observed a good, symmetrical series of images, the mirror *had* to be perfectly parabolic (Sidgwick, 1953: 63-64). It is likely that other telescope-makers also did a final star-test of a telescope. The process of waiting for a clear night, mounting the mirror in a telescope tube, testing, then dismounting the mirror in order to polish it further would have been very time-consuming. While this would not have been much of an issue for an amateur telescope-maker like Herschel, it would have been a great annoyance for a professional optician struggling to meet orders.

Herschel's efforts at producing ever larger, ever improved telescopes, was driven by his observational interests. Unlike most observational astronomers of the eighteenth and early nineteenth century who were interested chiefly in the positions of stars and motions of the planets, Herschel wanted to know something of the nature of the stars and nebulae. This kind of study required a type of telescope that was quite different to those used for positional astronomy, as done at the Royal Greenwich Observatory in England, for example. Positional astronomy required very sturdy mountings, finely-graduated scales for measuring small angles, and the ability only to see relatively bright stars. For such a purpose, the then-standard, small aperture, long focal-length refractor

was perfectly adequate. Herschel's work, on the other hand, required aperture and light-gathering power. In addition, his telescopes' relatively crude wooden mountings (e.g. see Figure 10) were perfectly adequate for his purposes (Lubbock, 1933: 64-65).

Besides producing telescopes for his own observational programs, Herschel also made telescopes for sale. Herschel was making the best large reflecting telescopes in the world around 1800, and the fame created by his discovery of the planet Uranus in 1781 without doubt encouraged many to purchase his instruments. Herschel could by no means be considered a mass-marketer of astronomical telescopes, even by the standards of his day, but he did offer more or less standard sizes at fixed prices. Records exist confirming the construction of at least 33 complete telescopes for sale, ranging in aperture from 5.5 inches to 24 inches. The most common size was the very convenient 7-foot focus telescope, which varied in aperture from 5.5 inches to 8.4 inches, though 6.7 inches was most typical; twenty-one 7-foot telescopes were made and sold between 1788 and 1812. The 10-foot focus telescopes were the next most popular (nine were produced), and were made with specula varying from 8.1 inches to 24 inches in diameter. The 14-foot, 20-foot, and 25-foot focus telescopes were each one-off items. Herschel stated in a letter dated 10 March 1794 that the prices of his complete telescopes—which appear not to have changed in over a decade—ranged from 100 guineas (£105 ca. 1800, which equates to about US\$8,500 in 2012) for the small 7-foot (6.7-inch mirror) to 8,000 guineas (US\$680,000) for a '40-foot' telescope with a 48-inch diameter mirror (Maurer, 1998: 15).

Purchasers of these telescopes were, to say the least, the elite of Europe. One of Herschel's best customers was none other than King George III, whose interest in astronomy led to Royal patronage of Herschel's research work; the King purchased several instruments as gifts for loyal subjects. Other buyers included King Carlos IV of Spain, Kaiser Franz I of Austria, Catherine the Great of Russia, Lucien Bonaparte, and the Grand Duke of Tuscany. How these telescopes were actually used is debatable, but they certainly served as "... showpieces." (Maurer, 1998: 4). Seven telescopes were purchased for use at various university and Government observatories around Britain and the rest of Europe. Individuals, such as the Italian astronomer Giuseppe Piazzi (1746–1826), purchased the balance (generally the smaller sizes), often for use in private observatories (see Gargano, 2012: 32).

While Herschel did in fact make telescopes for sale, the number sold was fairly small relative to the total number of mirrors made over his lifetime. Commercial telescope-making was clearly a sideline, something Herschel did to compensate himself for the time spent in producing telescopes for his own use. It was not a vocation, nor was it his means of livelihood. The fact that so many of Herschel's telescopes were made for prominent individuals might suggest that Herschel gained some status from his Royal patron. Compared to the commercial instrument-makers, Herschel could take his time and fabricate a series of superb instruments.

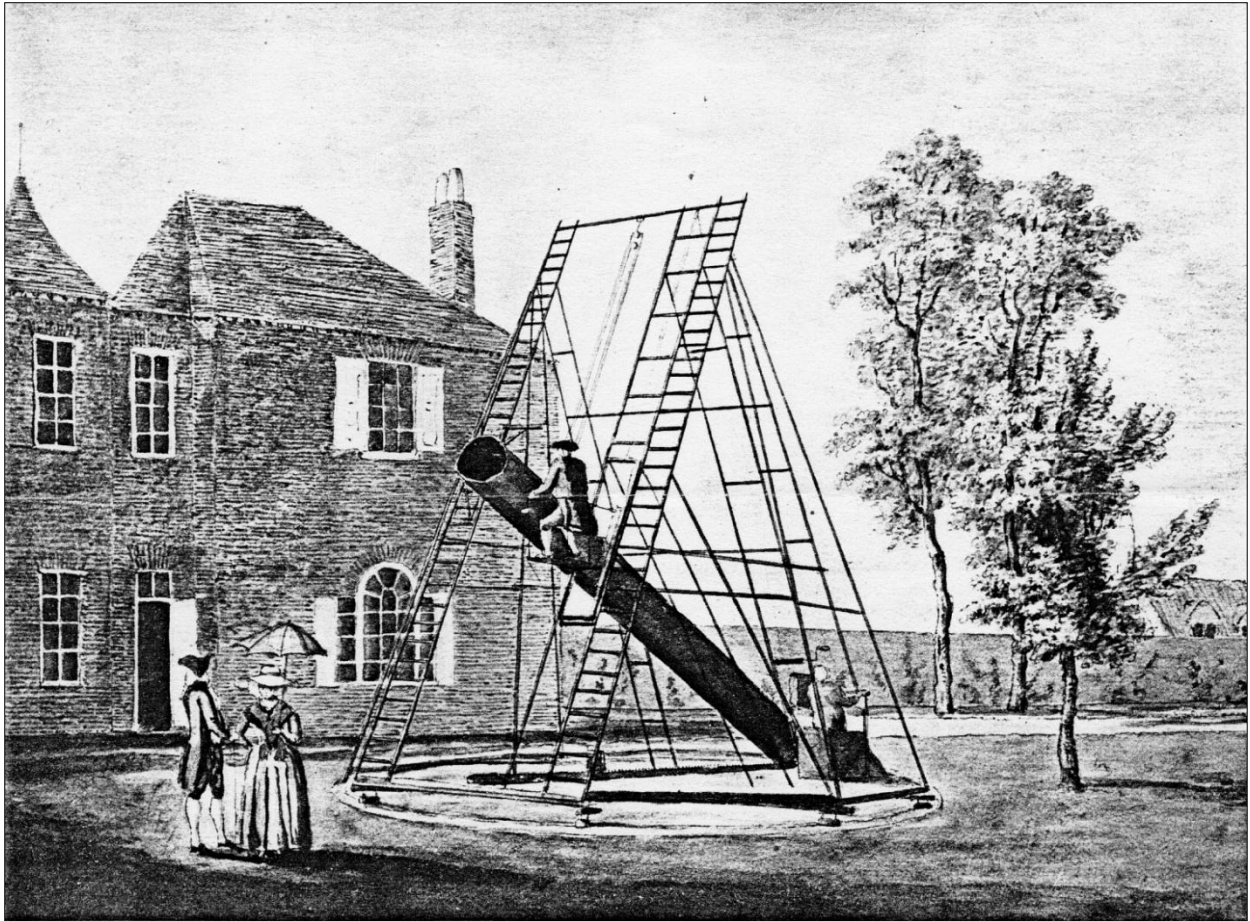


Figure 10: An example of one of Herschel's relatively crude wooden mountings (courtesy: Royal Astronomical Society).

6 CONCLUDING REMARKS

Although the reflecting telescopes of William Herschel represented a very high standard for such instruments, a level of both quality and size not surpassed until the 1840s, they were not entirely unique. Other astronomers were also involved in making reflecting telescopes for themselves in the early nineteenth century. One of them, the Reverend James Little, wrote a tract which was published in the *Journal of Natural Philosophy, Chemistry, and the Arts*, in 1807. Little's article provides considerable details of his own methods of casting specula, grinding, polishing and 'figuring' the mirror to the correct curve, as well as extremely detailed experimental analyses of problems of telescope design and fabrication (Little, 1807: 30-59, 84-100). Considering the seeming value of Little's treatise, it is remarkable that it fell into obscurity and later telescope-makers make no mention of it. Little's work is not mentioned in any later tracts on telescope-making, nor in King's *History of the Telescope*.

There were, in fact, a number of tracts available throughout the early nineteenth century for those interested in making reflecting telescopes. The mid-nineteenth century saw several large speculum-metal reflectors constructed by amateurs, primarily in Britain and Ireland. Some of these telescopes and their users made significant contributions to science, in particular the 6-foot diameter 'Leviathan of Parsonstown' (e.g. see Steinicke, 2012) which was constructed in 1845 by the wealthy William Parsons, 3rd Earl

of Rosse (1800–1867). Parsons conducted many experiments on producing large telescopes, but his improvements were gradual. While his giant telescope was spectacular in appearance, its construction did not greatly advance reflecting telescope technology.

William Herschel was just one of a number of gentleman-philosophers who read Smith's, Little's and other similar tracts on telescope-making. The German lunar observer Johann Hieronymus Schröter (1745–1816), along with Johann Gottlieb Friedrich Schrader (1763–1833) and a gardener named Gefken collaborated to produce a number of fine-quality telescopes modeled on Herschel's pattern. The Italian astronomer Carlo Isimbardi was likewise experimenting with large reflecting telescopes in the 1790s and 1800s (Gargano, 2012: 32-33). None of these individuals was a professional optician, although Gefken apparently sold some of his mirrors as a sideline. The majority of individuals producing large, high-quality reflecting telescopes at the end of the eighteenth century were amateur astronomers who had enough time and resources to experiment and perfect their instruments.

What is to be made of the great differences in optical quality between the various James Short telescopes evaluated by Willach? As stated previously, it could simply be that a person or persons unknown repolished Short's speculae and destroyed an otherwise fine surface. Willach (2001) claims that this is unlikely. There is also the fundamental problem with

Hadley's test depending so heavily on the skill of the optician; however, James Short was an extremely experienced and skilled telescope-maker, as demonstrated by the considerable number of fair to excellent telescopes that he produced.

It seems most likely that the answer to this quandary is that Short produced excellent optics when he had the time, or when luck prevailed, but when time was limited and the purchaser might not recognize the difference between a good telescope and a poor one, Short and other opticians could produce and sell inferior-quality goods. In his *Opticks*, Newton noted possible problems with London opticians around 1700:

Yet by this Experiment I satisfied my self that the Reflexion on the concave side of the Glass, which I feared would disturb the Vision, did no sensible prejudice to it, and by consequence that nothing is wanting to perfect these Telescopes, but good Workmen who can grind and polish Glasses truly spherical. An Objet glass of a fourteen Foot Telescope, made by an Artificer at London I once mended considerably, by grinding it on Pitch with Putty, and leaning very easily on it in the grinding, lest the Putty would scratch it. Whether this way may not do well enough for polishing these reflecting Glasses, I have not yet tried. But he that shall try either this or any other way of polishing which he may think better, may do well to make his Glasses ready for polishing by grinding them without that violence, wherewith our London Workmen press their Glasses in grinding. For by such violent pressure, Glasses are apt to bend a little in the grinding, and such bending will certainly spoil their Figure. To recommend therefore the consideration of these reflecting Glasses, to such Artists as are curious in figuring Glasses, I shall describe this optical Instrument in the following Proposition. (Newton, 1721: 94-95).

Considering how many telescope-makers, including William Herschel, mentioned Smith's *System of Opticks*, it seems highly unlikely that James Short and the better London instrument-makers would have been ignorant of this book. The test methods used by Hadley and Herschel were important in improving the reflecting telescope, but they were still clumsy and inexact. Texts on telescope-making by Smith, Little and others had been read by a number of telescope-makers, particularly gentlemen-philosophers and semi-professional opticians like Herschel.

The variable quality of James Short's telescopes, which ranged from poor to average to superb, can be understood without assuming the speculae had been re-polished by dilettante owners or incompetent opticians. The quality differences can be explained as simply having been due to production pressures. Although books such as Smith's *System of Opticks* were valuable conduits of knowledge, they had their limitations. Artisan telescope-makers such as Short appear to have known at least some of the techniques described by Smith, though they abandoned the time-consuming ones in favor of methods friendlier to the 'bottom-line'. On the other hand, gentlemen-philosophers like Hadley, Herschel, and Little fully embraced more sophisticated methods, particularly of testing, to produce qualitatively superior instruments. As a result, telescopes were either very expensive commercially-produced instruments of variable quality owned and used by wealthy individuals,

or they were hand-crafted by a small number of skilled gentlemen-philosophers. Major improvements were made in the quality of speculum metal reflecting telescopes in the eighteenth century. However, the numbers of truly high-quality, large-aperture instruments remained very small.

The limits to advances in telescope fabrication did not depend on scientific or technological knowledge as much as on the dissemination and use of such knowledge for purely economic reasons. Small telescopes, such as the vast majority produced by Short, would probably have been purchased by individuals who were largely ignorant of their true optical quality. Despite the availability of Smith's book, artisan opticians could not afford the perfection achieved by their gentleman-philosopher cousins.

7 NOTES

1. "Large pits" is a relative term as those generated in coarse grinding are only about $1/100^{\text{th}}$ of an inch across; these are quite noticeable and give the lens a frosted appearance. By the last stage of fine grinding the pits will have been reduced to less than $1/10,000^{\text{th}}$ of an inch and the lens will be nearly transparent.
2. Hadley's description concentrates on the physical layout of the tube and mounting. His telescope was of about 6 inches in aperture and had a focal length of $62\frac{1}{8}$ inches. In layout and accessories, Hadley's telescope is essentially the same as a modern Newtonian telescope. It had a 'slider' for adjusting the focus, a "... common Dioptrick [refracting] Telescope ..." (Hadley, 1723: 306) with cross-hairs as a finder, and three eyepieces magnifying 188 or $190\times$ ($1/3$ -inch FL), $208\times$ ($3/10$ -inch FL), and 228 - $230\times$ ($12/40$ -inch FL). The eyepieces were of a single-lens convex type.
3. The generally-accepted maximum surface error for a telescope mirror is $\frac{1}{4}$ of a wavelength in green light, or about ± 135 nanometers. The difference between a spherical surface and the correct parabolic one varies with both the diameter and the focal length of the mirror according to the formula $r^4/8R^3$, where r = the radius of the mirror (half of the diameter) and R = the radius of curvature (twice the focal length) of the mirror.
4. The lesser light-gathering power of early reflecting telescopes was due largely to the relatively low reflectivity of speculum metal. Even when freshly polished, a speculum metal mirror only reflected about 60% of the light falling on it. With two mirrors, as is the case with most reflecting telescopes, the total reflectivity would be 60% of 60% or only 36%. A reflecting telescope had only 25% of the light-gathering power compared to a refractor of equal size.
5. Although I think Willach's analysis of the Short telescope mirrors is largely correct, I strongly disagree with his statement "... that there are, in principle, only two methods of parabolizing mirrors in the sizes made by Short ...": the use of either a star-shaped tool or a ring-shaped polisher (Willach, 2001: 14-15). I have made about 160 telescope mirrors for Newtonian, Cassegrain and several types of unobstructed reflectors. These mirrors range from 2.0 to 16.0 inches in aperture, with focal ratios from $f/3.5$ to $f/30$. I am familiar

with the use of sub-diameter tools and long-stroke overhang polishing, which is the most commonly-used technique among those telescope-makers I know.

8 ACKNOWLEDGEMENTS

I am grateful to the Royal Astronomical Society for supplying Figure 10, and to my partner, Holly Hunt Strayer, for her support and editing assistance. Finally, I wish to thank Wayne Orchiston for helping with the revision to this paper.

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