

Chapter 5 Telescopes and Precision Observational Astronomy

The Micrometers of Hooke, Auzout and Wren

Hooke and Auzout, who had argued over Hooke's lens-grinding machine in 1665, began another disputation a couple of years later on the priority of the invention of the eyepiece micrometer. This instrument was to become an essential tool for precision astronomical measurement. It could be mounted on a telescope to measure, for example, the diameter of the planets or the angular distance of the fixed stars (Fig. 5-1). Hooke's interest in the device illustrates his role in the development and revival of precision observational astronomy.

It was Auzout who ignited the new controversy. He alluded to the eyepiece micrometer during his attack on Hooke's lens-grinding engine. He promised that he would publish his method to 'assign the Bigness of the *Diameter* of all the *Planets*'¹. In a letter to Oldenburg at the end of 1666, Auzout referred to this again². His letter was produced at the meeting of the Royal Society the following January³, and an extract was published in *Philosophical Transactions*. It reads:

'I did apply my self the last Summer to the taking of the *Diameters* of the Sun, Moon, and the other Planets, by a Method, which one M. *Picard* and my self have, esteem'd by Us the best of all those, that have been practis'd hitherto; since we can take the *Diameters* to *Second Minutes*, being able to divide one foot into 29000. or 30000 parts'⁴

While the construction of the device was not described in this article, an illustration in Auzout's *Manière* (Paris, 1667) suggests that he used an eyepiece micrometer as shown in Fig. 5-2⁵.

¹ 'Considerations of Monsieur Auzout upon Mr. Hooke's New Instrument for Grinding of Optick-Glasses', *Phil. Trans.*, 1 (1665), no. 4, pp. 57-69 (p. 63).

² Auzout to Oldenburg, 18 December 1666 (O.S.), *Oldenburg Corresp.*, 3, pp. 291-299.

³ *Birch*, 2, p. 139.

⁴ 'An Extract Of a Letter written Decemb. 28. by M. Auzout to the Publisher, concerning a way of his, for taking the Diameters of the Planets, and for knowing the Parallax of the Moon...', *Phil. Trans.*, 1 (1667), no. 21, pp. 373-375 (p.373). The misprinted number 24000 was amended to 29000 by reference to the original letter to Oldenburg (*Oldenburg Corresp.*, 3, p. 293).

⁵ See *ibid.*, plate I following p. 290. The full title of *Manière* is *Extrait d'une lettre de M. Auzout du 28 décembre 1666 à M. Oldembourg touchant la manière de prendre les diamètres des planètes & de sçavoir la parallaxe, ou la distance de la lune, comme aussi touchant la raison pourquoi dans la dernière éclipse de soleil, le diamètre de la lune parut plus grand vers la fin de l'éclipse qu'au commencement.*

At the Society meeting when the letter was introduced:

‘Dr. WREN and Mr. HOOKE having related to the society several ways, which they had known long before, of taking the diameters of the planets to seconds, were desired briefly to describe them, that so it might be signified to the Parisian philosophers, that it was a thing not at all new among the English’⁶.

In fact we have evidence that Wren had used an eyepiece micrometer as early as 1656. He wrote, probably to Petty, that:

‘we make the Tube an Astronomical Instrument to observe to Seconds, by which we take the Motions of Jupiter’s Satellites, and Saturn’s moon; and not only draw Pictures of the Moon, as Hevelius has done, but Survey her & give exact maps of her, & discover exactly her various Inclinations, and herein Hevelius’s Errors’⁷.

This proves that Wren employed the device in his younger years at Oxford. He also used eyepiece micrometers after he moved to London. The illustration in Hooke’s manuscript described Wren’s micrometer (Fig. 4-5, fig. 3 therein). Hooke clearly recorded that it was the device ‘Sr Chr Wren first contrived[:] A Rete or net of hairs strained in a frame to be made And placed in the focus of the object & Eye Glasses’⁸. The graticule could be used as a scale to measure distance. Hooke also sketched a visual image of the graticule as seen through the lens (Fig. 4-5, fig. 4 therein).

Hooke recorded in the same illustration (Fig. 4-5, fig 5) another micrometer which used two threads or hairs⁹. This was a divided sliding ruler with a rectangular aperture in the middle. Two threads were tensioned diagonally across the aperture. The part *eeee* was a socket in which the ruler slid, and the socket was mounted onto a telescope. As the ruler slid along in the socket, the distance between the images of the threads varied. By aligning the images of the threads over the object stars, the angular distance between the stars was measured by the scale on the divided ruler against the socket.

⁶ *Birch*, 2, p. 139.

⁷ Bennett (1973), p. 147.

⁸ Royal Society Classified Papers, vol. 20, no. 61, f. 131r.

⁹ *Ibid.* The same device was discussed in his Cutler Lecture *An Attempt to Prove the Motion of the Earth* published in 1674. See *Gunther*, 8, pp. 20-21.

In a lecture of 1693, which was published in *Philosophical Experiments*, Hooke supposed that Rheita ‘invented the Rete, or Mensurator, placed in the common Focus of the Glasses; which Sir *Christopher Wren* perfected’¹⁰.

Two micrometers, *i.e.*, a ‘Rete’ and a sliding ruler, were mentioned in *Micrographia* in 1665. Towards the end of the book, where Hooke considered the inflection of light by the atmosphere, he described ways to find the parallax of the planets. He wrote that long telescopes ‘should be fitted with a *Rete*, or divided Scale, plac’d at such a distance within the Eye-glass, that they may be distinctly seen, which should be the measures of minutes and seconds’¹¹. He also stated in *Micrographia* that he observed the sun &c ‘with a very good *Telescope*, fitted with a divided Ruler’¹².

Gascoigne’s Priority

In March 1667 Auzout’s priority was challenged by another Englishman, Richard Towneley. Towneley was struck by Auzout’s article on the micrometer in *Philosophical Transactions*, and wrote to the Royal Society to show that ‘Mr. GASCOYGEN had before the late civil wars both invented and used such an instrument’¹³. On 4 April Towneley’s letter was produced at the Royal Society by Croon, Gresham Professor of Rhetoric¹⁴. An extract of the letter was published in *Philosophical Transactions*¹⁵. Towneley wrote that Gascoigne made use of his micrometer:

‘not only for taking the Diameters of the Planets, and Distances upon Land; but had farther endeavour’d, out of its preciseness, to gather many Certainties in the Heavens; amongst which, I shall only mention one, *viz.* The finding the *Moons Distance*, from two Observations, of her *Horizontal* and *Meridional Diameters*’¹⁶.

¹⁰ *Philosophical Experiments*, p. 272. Wren’s ‘Rete’ was also mentioned in Sprat (1667), p. 314.

¹¹ *Micrographia*, p. 237.

¹² *Ibid.*, p. 230.

¹³ *Birch*, 2, p. 164.

¹⁴ Croon was the person who had told Boyle of ‘Towneley’s supposition’ of air six years before. See Webster (1965), pp. 480-481.

¹⁵ ‘An Extract Of a Letter, written by Mr. Richard Towneley to Dr. Croon, touching the Invention of Dividing a Foot into many thousand parts, for Mathematical purposes’, *Phil. Trans.*, 2 (1667), no. 25, pp. 457-458.

¹⁶ *Ibid.*, p. 457. For Gascoigne’s observations, see W. Gascoigne to Oughtred, c. February 1641, in Rigaud (1841), 1, pp. 35-59 (p. 52).

Towneley not only preserved Gascoigne's papers, but also 'The very Instrument he first made I have now by me, and two others more perfected by him'¹⁷. The instrument was 'not exceeding in weight, nor much in bigness, an ordinary Pocket-Watch, exactly making above 40000 Divisions in a *Foot*, by the help of two *Indexes*'¹⁸. Towneley sent the device to the Royal Society, and Hooke published its description in *Philosophical Transactions*¹⁹.

The illustration attached to Hooke's article shows the similarity of Gascoigne's micrometer to Auzout's (Fig. 5-3). The difference was that while Auzout used a cursor viewed through a slit to measure the distance, Gascoigne used parallel knife-edge indexes. Index *h* was propelled by a screw turned by a handle. The distance between the two indexes *h* and *i* was read off the circular scale on the brass plate *bbbb* which was 'divided into a 100 *equal* parts'²⁰.

When Gascoigne's micrometer arrived at the Royal Society on 11 July 1667, 'Mr. HOOKE mentioned, that he had invented an instrument of this kind, but upon another principle, which would perform the same things better, with more certainty and more ease'²¹. And when Hooke brought Gascoigne's instrument to the Society meeting on 25 July:

'Mr. HOOKE produced likewise an instrument of his own invention for the same purpose, but of more plain and easy use, it consisting of two threads and a ruler, whereby an inch is diagonally divided into five thousand parts...It was ordered, that Mr. HOOKE bring in an account of his instrument in writing, with a scheme of it'²².

However, at the beginning of the next year, Hooke had to be reminded to bring in the description. It was also ordered then 'that a copy of it should be sent to Mr.

¹⁷ *Phil. Trans.*, **2** (1667), no. 25, p. 457.

¹⁸ *Ibid.*, p. 458.

¹⁹ *Birch*, **2**, pp. 187-188 & 197-199; 'A Description of an Instrument for dividing a foot into many thousand parts, and thereby Measuring the Diameters of Planets to great exactness, &c', *Phil. Trans.*, **2** (1667), no. 29, pp. 541-544.

²⁰ *Ibid.*, p. 542. Alternative indexes with threads (Fig. 5-3, fig. 3 therein) were added to the illustration 'because it is conceived by some ingenious men, that it will be more convenient, instead of the Edges' (*ibid.*, p. 543).

²¹ *Birch*, **2**, p. 188. Hooke repeated similar claims several times. See *ibid.*, pp. 197, 199 & 204. His claim was also published in his article, 'More Ways for the Same Purpose, Intimated by M. Hooke', *Phil. Trans.*, **2** (1667), no. 25, p. 459.

²² *Birch*, pp. 188-189.

HEVELIUS'²³.

In Hooke's *Posthumous*, its editor Richard Waller printed a manuscript by Hooke entitled 'The divider for Hevelius'²⁴. The illustration attached to it (Fig. 5-4) shows that it used two movable threads connected to sliders on a rim. The two arms *cccc* opened equally by means of a connecting mechanism, and guided the sliders with the threads attached. The round hole at the top was mounted on the telescope, and the moving threads would be aligned at *ii* on the observed stars. Their angular distance was measured on a scale *gggg* below. Though it is not certain that the contrivance was identical to that which Hooke had in mind in 1667, it shared the same character: the use of two threads as indexes.

Fig. 5-1 shows how the different types of micrometer would appear to an observer using the telescope. *A* represents Gascoigne's knife-edge micrometer, and *C* represents Hooke's micrometers using threads or hairs. The micrometer represented at *B* was ascribed to Huygens. It appeared in his *Systema Saturnium* in 1659²⁵. Huygens placed a tapered metal bar in the telescope, and adjusted it so that one of the object stars appeared on each edge of the tapered bar. With this device he measured the diameters of the planets, the positions of their satellites, and so on.

Several astronomers had been interested in the eyepiece micrometer around 1660. But it is certain from the discussion above that the priority of its invention should be awarded to Gascoigne. Indeed, Gascoigne's priority in its invention and in its use to measure the diameters of the planets was reconfirmed in 1717 by William Derham (1657-1735) in his article in *Philosophical Transactions*²⁶.

Hooke and the Telescopic Sight

In the same article, Derham pointed out the priority of Gascoigne also for the invention of the telescopic sight. In reality, the main purpose of the article was to establish Gascoigne's priority on this rather than the eyepiece micrometer. Derham had already obtained Gascoigne's letters which Richard Towneley had preserved. Derham cited Gascoigne's letter of Christmas Eve of 1641, which recorded that Gascoigne wrote to Crabtree:

²³ *Ibid.*, p. 237.

²⁴ *Posthumous*, p. 498.

²⁵ *Oeuvres*, **15**, pp. 350-351; King (1955), p. 97; Helden (1980), pp. 154-155.

²⁶ 'Extracts from Mr. Gascoigne's and Mr. Crabtree's Letters, proving Mr. Gascoigne to have been the Inventor of the Telescopic Sights of Mathematical Instruments, and not the French', *Phil. Trans.*, **30** (1717), no. 352, pp. 603-610 (pp. 603-604).

'how he had applied his Telescopick Sights to a Sextant. Saith he, *Mr. Horrox his theory of the Moon I shall be shortly furnished to try. For I am fitting my Sextant for all manner of Observations, by two Perspicills with Threads*'²⁷.

We have already explained in Chapter 3 that the eyepiece micrometer and the telescopic sight, both of which Gascoigne invented, were taken up by natural philosophers at Oxford, probably through Oughtred until the 1650s. We also saw Wren's eyepiece micrometer earlier in this Chapter. Wren's son left a copy of Wren's manuscript on the telescopic sight 'Description of an Instrument for the observing Distances of fix'd Stars, and the Planets, and Appulses to the Moon; by two Telescopes join'd like a Sector, so as to give the true Angle of their Distances'²⁸.

Hooke mentioned Wren's telescopic sight in his Cutler Lecture *Animadversions on the First Part of Hevelius His Machina Coelestis* (hereinafter *Animadversions*), which was published in London in 1674²⁹. In it Hooke introduced a telescopic sight of 'Sr. *Christopher Wren's* invention, furnished with two Perspective Sights of 6 foot long each, which I made use of for examining the motions of the Comet, in the year 1665'³⁰.

Hooke left an illustration of the telescopic sight in his *Posthumous* (Fig. 5-5). He called it a 'double Telescope' and wrote again that it 'was invented by Sir *Christ. Wren*'³¹. He continued that 'The Instrument consists of two square Tubes or Boxes AB, and CD, which are each of them at B and D furnishe'd with a good Object-glass of six Foot'³². To measure the angular distance between two stars,

'the two Observators [*sic*] are to direct each of them his own Tube to the Star, which they have agreed upon to observe...And indeed, by means of a small additional contrivance, which I shall elsewhere shew, it may not only be made

²⁷ *Ibid.*, pp. 604-605.

²⁸ Wren (1750), p. 240.

²⁹ *Gunther*, 8, pp. 29-114. The details of its publication are discussed below.

³⁰ *Ibid.*, p. 78. On page 54 of the book Hooke referred to the same device, and wrote that 'I think I acquainted [it to] *Hevelius* some years since'. Hooke again mentioned Wren's invention of 'the angular Instrument, consisting of two Telescopes joined at a movable Joint' in his discourse of 1693. See *Philosophical Experiments*, p. 272. A description of the same device can be found in Hooke's manuscript at the Royal Society. See Royal Society Classified Papers, vol. 20, no. 61, f. 132r.

³¹ *Posthumous*, p. 502.

³² *Ibid.*

to distinguish Angles to Minutes but to Seconds also'³³.

Hooke not only used Wren's telescopic sight, but also devised his own. He seems to have started the work around 1665. Hooke showed a sight to the Society meeting on 22 February the next year, just before the suspension of meetings due to the plague³⁴. The record of the meeting reads:

'Mr. HOOKE produced a new small quadrant contrived by himself, to make, by the means thereof, both celestial and terrestrial observations with more exactness than by the largest instrument, that had been hitherto publicly known. This quadrant was only of 17 inches radius, being by the contrivance of a small roller, that moved upon the limb of it, made so accurate, that each degree was actually distinguished into 60 minutes, each of which minutes being about one third of an inch long, was actually divided into six parts, denoting every 10 seconds in a minute'³⁵.

The device was probably the one later published in *Animadversions* (Fig. 5-6)³⁶. As fig 1 of Fig. 5-6 shows, this consisted of two telescopes connected at the centre of a part-circle: one, *ap*, was fixed, and the other *cc* was propelled by a small roller on the limb. Both tubes had 'cross Clews at the Focus'. To measure the angular distance of two stars, the fixed tube was directed to one target star and the movable tube to the other, turning the roller at the limb with a dial mechanism. The images of the stars could be observed simultaneously through the hole at the joint by means of diagonal mirrors illustrated in fig. 12 of Fig. 5-6. When the images of the two stars were seen to overlap precisely, the angular distance of the stars was read off from the number of revolutions of the dial. The device could be used by a single observer, though it was an adaptation of Wren's double telescopes which needed two observers³⁷.

³³ *Ibid.*, pp. 502-503.

³⁴ The activities of the Royal Society were suspended from 28 June 1665 to 21 February 1666. See *Birch*, 2, pp. 60, 63 & 65.

³⁵ *Ibid.*, p. 18.

³⁶ *Gunther*, 8, pp. 82ff. A modified contrivance was discussed in *Helioscope* (*ibid.*, pp. 129ff).

³⁷ Another difference was the connecting part: Wren joined the two telescopes at the object lens end, Hooke at the eyepiece end.

Hooke vs. Hevelius

Hooke and Hevelius began a dispute about the telescopic sight in 1668. The plain sight (or open sight), which is shown in Fig. 5-7, had been used for astronomical measurement since Tycho³⁸. The angular distance of stars was measured by a scale at the limb. Hevelius defended the use of the traditional plain sight, while for precision astronomical measurement Hooke promoted the telescopic sight which was to become an essential instrument for positional astronomy.

In 'The Life of Dr. Robert Hooke', the first biography of Hooke, Richard Waller wrote that an 'unhappy Dispute between Monsieur *Hevelius* and *Hooke* concerning the preference of Plain and Telescopic Sights for Astronomical Instruments' broke out not long after the optical controversy between Hooke and Newton in 1672³⁹. In reality however, the dispute had already started before Newton's debut at the Royal Society, and it continued until the mid-1680s. Hooke and Hevelius had opposing views on which instrument to use for precision measurement.

The controversy was occasioned by their exchange about the long telescope Hevelius ordered from England. It was in 1669 that the fifty-foot telescope, made by Cock, was sent to him. Before that, in his letter of February 1667, Hooke wrote to Hevelius explaining how to mount it, and recommended the use of 'telescopicall sights' for 'determining the Diameters & parallaxes of the planets & for finding the positions & Distances of the smaller fixt stars'⁴⁰.

Hevelius was interested in Hooke's description and wrote to Oldenburg that 'I might receive a full description of those telescopic sights fitted to sextants for measuring stellar distances'⁴¹. But Hooke did not send the description because 'Mr. Hooke has been extremely busy in surveys for the rebuilding of the city'⁴².

Oldenburg communicated Hooke's description to Hevelius in a letter on 11 May the next year. According to it Hooke claimed that:

'Telescopic sights so greatly surpass those commonly used in instruments of all kinds, whether quadrants, sextants, or levels, especially for any kind of celestial observation...The way of applying them is very easy, since nothing more need be done than to apply six-foot telescopes to those instruments in

³⁸ Chapman (1983), p. 134; *Gunther*, **8**, p. 8.

³⁹ *Posthumous*, xv.

⁴⁰ Hooke to Oldenburg, c. 20 February 1667, *Oldenburg Corresp.*, **3**, pp. 347-349 (p. 348); Oldenburg to Hevelius, 27 February 1667, *ibid.*, pp. 350-354 (pp. 351-352 & 354).

⁴¹ Hevelius to Oldenburg, 11 October 1667 (O. S.), *ibid.*, pp. 517-520 (pp. 518 & 519).

⁴² Oldenburg to Hevelius, 31 January 1668, *ibid.*, **4**, pp. 134-138 (pp. 135 & 137).

place of the fixed sights and of the movable sights which in the ordinary instrument swing around [the arc]. The telescopes for the purpose should be very well made with a wooden tube of square section, having a drawtube at the end near the eye where the convex eye-lens and the graticule, or pointer, are to be mounted'⁴³.

From the description it is apparent that the telescopic sight was of a similar design to Wren's double telescopes which appeared in Hooke's manuscript entitled 'The divider for Hevelius' (see above and Fig. 5-5). Indeed, both used 'six-foot telescopes' with 'square section', though in the manuscript Hooke omitted how to apply the double telescopes to measuring arcs.

The latter half of the description was to 'illustrate the method of adjusting a quadrant' or a measuring arc to the telescopic sight. Oldenburg attached a diagram (Fig. 5-8) to it, and wrote:

'let *ief* be the quadrant, *ie* and *if* its two tubes placed as nearby as possible at right angles. Let *a* and *b* be the two objects first viewed upon the distant horizon, *a* being seen through *ie* and *b* through *if*. Then, keeping the centre fixed at *i* and the arms fixed at the same angle, move the quadrant to *fig* so that *ie* may be now in the line *if* and the same object be seen through it, and so that *if* may be at *ig* and *c* seen through it'⁴⁴.

The same procedure was repeated three times, and if the tubes made an exact right angle the tube first directed to *b* (*if*) should then point to *a*.

The detailed description of the calibration of a quadrant demonstrates that Hooke was familiar with the use of the instrument for angular measurement. But Hevelius would have preferred to learn the advantage of telescopic over plain sights, and on this point Hooke simply wrote that, with the telescopic sight, 'an instrument of one span radius can be made much more accurate than another of sixty-foot radius' with the plain sight⁴⁵.

In the following month, June 1668, Hevelius sent to Oldenburg a letter disputing the reliability of telescopic sights. He wrote that, to measuring arcs,

⁴³ Oldenburg to Hevelius, 11 May 1668, *ibid.*, 393-398 (pp. 393 & 396).

⁴⁴ *Ibid.*, pp. 395 & 397. At the beginning of the quoted passage, Oldenburg mistakenly wrote *ef* for *if* (see *ibid.*, note 6, p. 398). The correction is the author's.

⁴⁵ *Ibid.*, pp. 393 & 396.

'telescopes cannot be so firmly fixed in any way that they will not shift, even if they are first calibrated with all diligence by that technique of circling the whole horizon...I am as yet reluctant to declare whether an instrument of a single span radius can be much more exact than the best of those having ordinary sights, even though of 60-foot radius. For many things seem most certain in theory, which in practice often fall far enough from truth. If any one will present me with the observations, taken with these instruments furnished with telescopic sights, of the distances between some fixed stars between the ecliptic and the equator (such as the distance of the bright star in aries from Aldebaran; of Aldebaran from Pollux; of Pollux from Regulus; of Regulus from Spica Virginis; of Spica Virginis from the northern star in the left and of Serpentarius; from this star to Aquila; from Aquila to Marcab, and fro Marcab to the bright star in aries), I will immediately give my judgement of the question'⁴⁶.

It was actually in the same letter that Hevelius asked for Hooke's advice on choosing the long telescope he was ordering, so he remained circumspect in his criticism of Hooke's claims.

Hooke soon sent Hevelius a counterargument via Oldenburg. He said rather forthrightly that:

'as to the manner of attaching these telescopic sights to instruments (whether quadrants or sextants or others), it cannot be denied that a square wooden tube of a convenient length can as well be fitted to that instrument as the common pinnules [sights] can, and that such a square tube may move about the centre of the instrument as exactly as the common movable pinnule, and be furnished with an index adapted to a divided scale'⁴⁷.

Hooke also explained several methods of reading at the limb the angular distance of the observed stars:

'As firstly by means of a screw movable upon the limb of the instrument together with the index; or secondly by means of a certain cylinder, likewise moving round the limb of the instrument together with the index; or thirdly

⁴⁶ Hevelius to Oldenburg, 3 June 1668 (O.S.), *ibid.*, pp. 443-449 (pp. 445-446 & 448).

⁴⁷ Oldenburg to Hevelius, 30 July 1668, *ibid.*, pp. 576-581 (pp. 576-577 & 579).

by means of a certain sliding rule and twisted thread, observed with a lens'⁴⁸.

In the same letter, Hooke raised an important point of discussion, that the use of the instrument had the advantage of extending the limits of human perception. He emphasised that:

'the naked eye is barely able to distinguish with confidence an angle of one whole minute, whereas the eye furnished with a telescope can easily distinguish any number of seconds of arc, or even a single second'⁴⁹.

Hooke had raised the limitations of human sight in the exchange with Auzout three years before on the possibility of seeing creatures on the moon. Oldenburg had written then to Auzout that Hooke showed 'while explaining some mathematical instruments, that very few persons can distinguish an angle less than one minute'⁵⁰ (see p. ** of the last Chapter).

In October 1668, Oldenburg wrote to Hevelius that, as for telescopic sights, Hooke 'persists in his view that they are (your doubts notwithstanding) ten, twenty, thirty, or forty times more accurate than the common sights'⁵¹.

Hevelius sent two letters in the following two months challenging Hooke's claim. He repeated his belief that the distances between stars could not be observed accurately with the telescopic sight. The reason was the small telescopes used:

'there is no way by which they can be pointed precisely enough, because of the reduced distance between the sights, even though the instrument may be imagined as being divided into the most minute parts; since the greater the interval between the sights, the more exactly we can measure the angle between objects'⁵².

He added a specifically Polish difficulty that, when using telescopic sights in winter, the lenses 'acquire a film or coating from, or become spotted by, the vapour emitted from the mouth and eyes'⁵³.

⁴⁸ *Ibid.*, pp. 577 & 579.

⁴⁹ *Ibid.*, pp. 576 & 579.

⁵⁰ Oldenburg to Auzout, 23 July 1665, *ibid.*, **2**, pp. 439-433 (pp. 441 & 443).

⁵¹ Oldenburg to Hevelius, 28 October 1668, *ibid.*, **5**, pp. 112-117 (pp. 113 & 115).

⁵² Hevelius to Oldenburg, 19 November 1668 (O.S.), *ibid.*, pp. 181-190 (pp. 182 & 186).

⁵³ *Ibid.*

To confirm the ability of the plain sight, Hevelius appealed to the exactness of his own observations:

‘Indeed, without boasting, I can divide intervals with my instruments not only to the accuracy of whole minutes, but even to the fifth or tenth part of a minute, or sometimes to single seconds of arc, as many thousands of observations made by myself clearly show’⁵⁴.

Even if Hevelius was convinced of the advantage of the plain sight, his mind was opened to practical comparison of it with the telescopic sight. Indeed, Hevelius asked Oldenburg to send a telescopic sight of the best type⁵⁵, but his request went unfulfilled even when repeated⁵⁶. The argument between Hooke and Hevelius was suspended for a while.

Controversy on *Machina coelestis*

Their controversy resurfaced when Hevelius published *Machina coelestis, pars prior* in 1673. Hevelius had been preparing the work for a long time, and the academic world was expecting its publication; as Oldenburg wrote to him in 1669, ‘The whole learned world burns with a desire to see your *Machina coelestis*’⁵⁷.

In the latter part of Chapter 14 of *Machina coelestis, pars prior*, Hevelius explained why he did not use telescopic sights. He basically repeated the argument he had written to Hooke: many things which theoretically seemed most certain did not work in practice, it was difficult to fix square tubes firmly to measuring arcs, and the cross thread pointer set into them could also shift. The error of the telescopic sight would be not less than seconds, and often minutes⁵⁸. Therefore observation with the telescopic sight would not surpass that with the plain sight, with which he had achieved an accuracy of five or ten seconds in his observations over thirty years⁵⁹. The

⁵⁴ Hevelius to Oldenburg, 11 December 1668 (O.S.), *ibid*, pp. 241-246 (pp. 241 & 244).

⁵⁵ *Ibid.*, pp. 182 & 187. Hevelius wrote here that he could not follow Hooke’s description of Towneley’s eyepiece micrometer because it was in English. He grumbled that ‘All foreigners wish that your *Philosophical Transactions* might be printed in Latin as soon as possible’ (*ibid*).

⁵⁶ Oldenburg to Hevelius, 2 August, 1669, *ibid.*, 6, pp. 161-171 (pp. 167 & 170); Hevelius to Oldenburg, 25 June 1670 (O.S.), *ibid.*, 7, pp. 44-50 (pp. 45 & 48); Hevelius to Oldenburg, 21 April 1671 (O.S.), *ibid.*, 8, pp. 3-8 (pp. 4 & 6); Oldenburg to Hevelius, 9 November 1671, *ibid.*, pp. 349-353 (pp. 351 & 353).

⁵⁷ Oldenburg to Hevelius, 23 January 1669, *ibid.*, 5, pp. 352-356 (pp. 353 & 355).

⁵⁸ Hevelius (1673), pp. 293-295.

⁵⁹ *Ibid.*, pp. 298-299.

plain sight was well established, and there was no reason to reject it⁶⁰. Although Hevelius did use the refracting telescope for astronomical observations, he was sceptical of its value for precision astronomical measurement.

When *Machina coelestis, pars prior* was published in August 1673, Hevelius immediately sent several copies to England⁶¹. Hooke's diary records that he delivered a declamation lasting almost one hour against Hevelius's work at the Cutler Lecture of 11 December of that year⁶².

At the Royal Society meeting on 15 January 1674, Hooke conducted an experiment to demonstrate 'that we cannot by the naked eye make any astronomical or other observation to a greater exactness than that of a minute'⁶³. He prepared a ruler divided into parts which appeared to subtend one minute from a certain distance. None of the people present were able to distinguish those parts with the naked eye. Clearly the purpose of the experiment was to show the limitations of the plain sight Hevelius advocated. The same experiment was repeated at the next meeting⁶⁴.

Just before the experiment, Oldenburg wrote to Hevelius that 'there are those among us [the members of the Royal Society], of whom Mr. Hooke is one, who despite what you have written on p. 294 against telescopic sights' still persist in using them⁶⁵. John Flamsteed, a future member of the Society who was elected Astronomer Royal the following year⁶⁶, was also critical of Hevelius, even though he was not on good terms with Hooke⁶⁷. In his letter to Cassini on 7 July 1673, which was published in *Philosophical Transactions*, Flamsteed wrote:

'We have indeed heard that the most celebrated Johannes Hevelius has undertaken the restitution of the fixed stars, but since he is reported to use bare sights without lenses, [we can expect] from him positions very little more correct than those which Tycho left, except where he was especially wildly

⁶⁰ *Ibid.*, p. 295.

⁶¹ Hevelius to Oldenburg, 13 August 1673, *Oldenburg Corresp.*, **10**, pp. 139-143 (pp. 140-142).

⁶² *Diary 1672-1680*, p. 74.

⁶³ *Birch*, **3**, p. 120.

⁶⁴ *Ibid.*, p. 121.

⁶⁵ Oldenburg to Hevelius, 9 January 1674, *Oldenburg Corresp.*, **10**, pp. 428-431 (pp. 429-430).

⁶⁶ Flamsteed was elected fellow of the Society on 8 February 1677, two years after his appointment as Astronomer Royal (*Birch*, **3**, p. 333). This seems to reflect the low prestige of the Observatory in its early days.

⁶⁷ For Flamsteed's attitude to Hevelius, see MacPike (1937), pp. 78ff. For Flamsteed's relationship with Hooke, see Johns (1997), pp. 81-82; Inwood pp. 179-180.

wrong. I wish that this correction were made by you in France'⁶⁸.

Flamsteed maintained his faith in the telescopic sight. He employed the sextant with telescopic sights for observation at Greenwich Observatory from 1676.

Hevelius responded to his critics in England. He expressed pride in his observational achievements with the plain sight, and wrote that:

'if I had undertaken that whole business with telescopic sights then not only would I have wasted many years in making trials but beyond doubt I would have lost hope for a variety of reasons (of which this is not the place to speak). Hence I congratulate myself that I have never yet gone over to that opinion, that I have completed everything by my own method'⁶⁹.

He stressed the importance of comparing the capabilities of plain and telescopic sights in prolonged practical observations:

'When at some time we shall have observations from both parties continued over a space of 20 or 30 years, that is to say those taken from the heavens with telescopic sights and those taken only with our [plain] sights, the matter will be much clearer'⁷⁰.

Hevelius even made a cynical point by reference to an astronomer in Paris. The man used telescopic sights, therefore 'as yet the elevation of the pole at Paris has not been defined to some whole minutes'⁷¹.

Hooke's *Animadversions*

In response to Hevelius's letter, Oldenburg wrote back to him on 23 March 1674 that 'Mr. Hooke for many strong reasons prefers telescopic sight to those common ones adopted hitherto, chiefly because of their accuracy, which is much beyond

⁶⁸ Flamsteed to Cassini, 7 July 1673, Flamsteed (1995), pp. 210-220 (pp. 214 & 220); 'Johannis Flamstedii Epistola ad clarissimum Cassinum', *Phil. Trans.*, **8** (1673), no. 96, pp. 5094-6000 (p. 6000). Note that there are apparently misnumbered pages throughout most of the letter in *Philosophical Transactions*.

⁶⁹ Hevelius to Oldenburg, ?16 March 1674, *Oldenburg Corresp.*, **10**, pp. 514-525 (pp. 516-517 & 521). An extract of the letter was published in *Phil. Trans.*, **9** (1674), no. 102, pp. 27-29.

⁷⁰ *Oldenburg Corresp.*, **10**, pp. 517 & 521-522.

⁷¹ *Ibid.*, pp. 516 & 520-521.

expectation'⁷². Hooke presented the reasons for his claim in his Cutler Lecture *Animadversions on the First Part of Hevelius His Machina Coelestis*.

Hooke finished writing the work on 10 December 1674, and the book was sent to Hevelius by Oldenburg the following April with the comment that 'You will perhaps resent the comments which Mr Hooke has made on the first part of your *Machina Coelestis*'⁷³.

Hooke's *Animadversions* to Hevelius started as follows:

'though I doubt not in the least but that he hath by his own extraordinary diligence, care and cost, corrected several mistakes and errors committed by the assistants of the Noble *Ticho*: yet I am not satisfied that his Instruments are capable of making Observations more accurately then those of Ticho'⁷⁴.

He cited three reasons: Hevelius used measuring arcs of similar size to Tycho's; both applied the plain sight; and though Hevelius developed a new way to divide the scale, its accuracy did not surpass Tycho's⁷⁵.

Then Hooke proceeded to the point of the limitations of the human eye. He wrote that 'the eye can hardly distinguish minutes in the object'⁷⁶, so that in using the arc furnished with the plain sight, anyone would 'find himself able to do as much with an instrument of three foot, as with one of threescore'⁷⁷. Therefore it would be useless to make a finer division with a larger arc.

To demonstrate the limited resolution of the naked eye, he proposed an experiment with a sheet of paper on which parallel lines or divisions were drawn (Fig. 5-9, fig. 28 therein). The sheet was fastened to a wall, and the observer was asked to step back from it until his eyes could no longer distinguish those divisions. The subtended angle could be calculated easily from the distance⁷⁸.

From detailed examination of the arc Hevelius used, Hooke concluded that:

'it was wholly impossible for him [Hevelius], with all or any of the Instruments he hath described, to make any one of these Observations, to the

⁷² Oldenburg to Hevelius, 23 March 1674, *ibid.*, pp. 531-533 (pp. 531-532).

⁷³ Oldenburg to Hevelius, 14 April 1675, *ibid.*, pp. 278-288. See also note 2 to the letter.

⁷⁴ *Gunther*, **8**, p. 38.

⁷⁵ *Ibid.*

⁷⁶ *Ibid.*, p.39.

⁷⁷ *Ibid.*, p. 44.

⁷⁸ *Ibid.*

certainty of 30 seconds⁷⁹

Hooke asserted that there was less need to rectify the telescopic sight than the plain sight, and that Hevelius's rejection, regardless of Hooke's exhortation of it for about nine years, might have originated in prejudice⁸⁰. Whereas Hevelius thought that no trial had ever been made of telescopic sights, Hooke affirmed his experience. He wrote that he had by him several instruments:

'and particularly one of Sr. *Christopher Wren's* invention, furnished with two Perspective Sights of 6 foot long each, which I made use of for examining the motions of the Comet, in the year 1665⁸¹.

Though Hevelius often appealed to his experience, this rather proved the need of long practice and much experience to get used to the plain sight⁸². Hooke insisted that:

'I do now venture to affirm, without staying 10 years or more to make Observations, that I can do more with a Quadrant, Sextant or Octant, of 1 foot Radius, furnished with Telescopical Sights and Screws, then can possibly be done with any other Instrument, furnished only with Common Sights, though 10, 20, 30, nay threescore foot Radius⁸³.

The reason that 'the Latitude of *Paris* is not yet exactly known' was that the telescopic sight was unknown⁸⁴. While Hooke praised Hevelius's 'care and diligence, in the performing a Work so highly usefull to Astronomy and Navigation'⁸⁵, he wrote:

'But yet I would not have the World to look upon these as the bound or *non ultra* of humane industry, nor be perswaded from the use and improvement of Telescopical Sights'⁸⁶.

⁷⁹ *Ibid.*, p. 74.

⁸⁰ *Ibid.*, p. 78.

⁸¹ *Ibid.*

⁸² *Ibid.*, p. 102.

⁸³ *Ibid.*, p. 79.

⁸⁴ *Ibid.*

⁸⁵ *Ibid.*, pp. 79-80.

⁸⁶ *Ibid.*, p. 80.

Hooke went so far as to suggest that, if Hevelius had adopted the telescopic sight for his observations, he could have published 'a Catalogue ten times more accurate' with much less effort⁸⁷.

After his scathing criticism of Hevelius, Hooke allocated more than ten pages of *Animadversions* to describing his own telescopic sight, which we have already seen (Fig. 5-6)⁸⁸. The instrument was set by a screw on its moving arm. He had described the instrument before in words, but this time he included an illustration.

Hooke also gave some explanation of how to calibrate the instrument, and this clearly showed that he was experienced in its use. Indeed Hooke wrote that if anyone wanted a similar instrument 'he may employ Mr. *Tompion*, a Watchmaker in *Water-Lane* near *Fleetstreet*; this person I recommend, as having employ'd him to make that which I have'⁸⁹.

Hevelius's previous restraint evaporated when he read Hooke's *Animadversions*. His agitation was clear in his letter to Oldenburg after its publication⁹⁰. It was an understandable outburst of anger from a man whose lifelong reputation for accuracy of observation was impugned.

In the letter, Hevelius first objected to the fact that Hooke had published *Animadversions* in English instead of Latin⁹¹. Then he pressed his main advantage. He said that 'In my writings I have but set down, always, whatever I have achieved'⁹², but while Hooke

'ought to demonstrate his discoveries by observations already made by himself, he does the business in an abundance of mere words and grandiloquent reasons...nothing concerns him more than that he should persuade me and the whole world...not only that he can determine all observations to single seconds but also that his are thirty, forty, fifty, even sixty times more accurate than mine and all those of others, or any ever made or to be made by my method; when nevertheless his whole case rests upon empty discourse and pretence'⁹³.

Hevelius repeated that 'what is needful is a multitude of observations made by

⁸⁷ *Ibid.*, p. 38.

⁸⁸ *Ibid.*, pp. 82ff.

⁸⁹ *Ibid.*, p. 90.

⁹⁰ Oldenburg to Hevelius, 21 August 1675 (O.S.), *Oldenburg Corresp.*, 11, pp. 458-475.

⁹¹ *Ibid.*, pp. 459 & 467.

⁹² *Ibid.*, pp. 460 & 468.

himself⁹⁴ and asserted that it was unworthy to despise and scorn the observing labours performed and at present still to be performed by others⁹⁵.

Hevelius endeavoured to moderate his anger in this lengthy letter. He stated that he actually did not like quarrelling. A decade later, the letter was included in his final work published within his lifetime, *Annus climactericus*⁹⁶. But, at the Royal Society meeting of 24 February 1686, 'Mr. HOOKE read a paper vindicating himself from some injuries, which he conceived done him by Mr. HEVELIUS in his *Annus Climactericus*⁹⁷ even though at the last meeting he had performed an experiment to show the advantage of telescopic over plain sights⁹⁸.

Halley's Visit to Hevelius

Hooke and Hevelius had never agreed about the capabilities of the telescopic sight. But its advantage was proved quite soon, when Flamsteed achieved observation to an accuracy of about ten seconds, which was superior to that of Hevelius⁹⁹. Flamsteed began his observation at Greenwich Observatory in 1676, and he published the results at the beginning of the eighteenth century. Helden wrote that:

'The application of telescopic sights to measuring instruments such as quadrants resulted in an increase in accuracy of an order of magnitude in measuring angular separations, from Tycho's 4 minutes of arc to Flamsteed's 10 seconds of arc'¹⁰⁰.

However, despite Hooke's belief, Hevelius achieved greater accuracy than Tycho with the plain sight. It was between about 30 seconds and a minute, halfway between Tycho and Flamsteed¹⁰¹. The accuracy of Hevelius's observation was made known in England by Halley, who visited Hevelius's observatory at Danzig in 1679.

Halley already had considerable experience of positional astronomy, as he went to St. Helena in 1676, when he was twenty years old, to compile a stellar

⁹³ *Ibid.*

⁹⁴ *Ibid.*

⁹⁵ *Ibid.*, pp. 461 & 469.

⁹⁶ Johannes Hevelius, *Annus climactericus* (Danzig, 1685), pp. 54-60. Wallis introduced the book in *Phil. Trans.*, **15** (1685), no. 175, pp. 1162-1183.

⁹⁷ *Birch*, **4**, p. 461.

⁹⁸ *Ibid.*, p. 459.

⁹⁹ Chapman (1983), p. 134.

¹⁰⁰ Helden (1974a), p. 57.

¹⁰¹ Chapman (1983), p. 134.

catalogue of the southern hemisphere. Halley was elected fellow of the Royal Society in 1678, in the same year that he published *Catalogus stellarum austroraliium* in London.

Hevelius was curious about the young Halley who had produced the austral catalogue, while Halley wanted to meet the famous astronomer at Danzig and see his instruments and the manner of his observation¹⁰².

Hevelius welcomed Halley on his arrival at Danzig on 26 May 1679 (N.S.)¹⁰³. Halley stayed there for six weeks, until 8 July. Halley had used a 5½-foot sextant with telescopic sights at St. Helena¹⁰⁴, so he was qualified to compare plain sights with telescopic sights. The day Halley arrived, Hevelius showed him his observations.

Halley wrote to Jonas Moore, and the content of his letter was reported by Hooke to the Royal Society meeting of 5 June 1679. Hooke said:

‘that he, Mr. HALLEY, had seen Mr. HEVELIUS’S observations and instruments, and found them very extraordinary, but all with common sights: that he had seen Mr. HEVELIUS make observations with those instruments of the distance of two fixed stars, and that they were capable of making them to half a minute; but that he was not able to do this nearer than to a minute’¹⁰⁵.

The last part of this accorded with Hooke’s experimental result that the human eye could not discern an angle of less than a minute. However, Hevelius’s observations demonstrated paradoxically that the naked eye could resolve to less than a minute when the angle observed was moderately larger than a minute.

Halley sent a letter to Flamsteed dated 7 June from Danzig. He wrote:

‘as to the distances measured by the Sextant, I assure you I was surpriz’d to see so near an agreement in them, and had I not seen, I could scarce have credited the Relation of any; Verily I have seen the same distance repeated severall times without any fallacy agree to 10” ’¹⁰⁶.

¹⁰² MacPike (1937), pp. 84-85. MacPike suggested here that Flamsteed could have acted as intermediary between Halley and Hevelius. Indeed, ‘Halley began positional astronomy assisting Flamsteed in 1675’ (*DSB*, ‘Halley’, 6, p. 69).

¹⁰³ The description below mainly depends on MacPike (1937), pp. 85-89; *Phil. Trans.*, 15 (1685), no. 175, pp. 1164-1170. See also Cook (1998), pp. 92ff.

¹⁰⁴ MacPike (1937), p. 39.

¹⁰⁵ *Birch*, 3, p. 488.

¹⁰⁶ Halley to Flamsteed, 7 June 1679, Flamsteed (1995), pp. 694-696 (p. 694).

Hevelius made observations with Halley's instrument furnished with telescopic sights. But he could not 'make observations with the accuracy and that readiness, as with his own'¹⁰⁷. When Halley departed from Danzig, he left a letter of attestation to confirm the accuracy of Hevelius's observations¹⁰⁸.

Soon after Halley's departure, Hevelius suffered a great tragedy. His house caught fire on 26 September 1679, and his observatory was destroyed¹⁰⁹. Fortunately, his observational data of fixed stars, his correspondence with eminent natural philosophers, and all the Kepler manuscripts he had were saved. Unbound books produced by Hevelius were lost, while the bound volumes escaped the fire. Hevelius had printed his *Machina coelestis, pars posterior* in February of that year, but not many had been sold and 'fewer than 100 copies survived the fire'¹¹⁰. He was able to rebuild the observatory and equip it with the necessary instruments, 'though [they were] much inferior to those incomparable ones that perished by the fire'¹¹¹.

Levels and Equatorials

The main purpose of Hooke's *Animadversions* was, of course, to criticise Hevelius's adherence to the plain sight, and to promote the use of the telescopic sight. But the book also discussed other devices for astronomical observations. Among them was a water level for setting measuring arcs exactly perpendicular (Fig. 5-9, fig. 24 therein)¹¹². It consisted of a glass tube with a bulge in the middle. The tube was filled with distilled water containing 'Aqua-fortis or spirit of Niter' as antifreeze, leaving a bubble of air above the liquid¹¹³. Hooke claimed such accuracy for the water level that it 'can hardly be performed by the ordinary way of Plumbets, without hanging from a vast height'¹¹⁴.

Hooke had mentioned the level as early as 28 November 1666 at a Royal Society meeting¹¹⁵. The following month Wren also produced a description of his level. It was a concave glass on which a drop of quicksilver was placed, and 'when the

¹⁰⁷ *Phil. Trans.*, **15** (1685), no. 175, p. 1168.

¹⁰⁸ *Ibid.*, pp. 1168-1169.

¹⁰⁹ For the details of the event, see a letter sent by Peter Wyche printed in MacPike (1937), pp. 108-111. The letter was presented to the Royal Society meeting on 18 December 1679. See *Birch*, **3**, p. 519.

¹¹⁰ *DSB*, **6**, p. 362.

¹¹¹ *Phil. Trans.*, **15** (1685), no. 175, p. 1163.

¹¹² *Gunther*, **8**, pp. 97ff.

¹¹³ *Ibid.*, pp. 97-98.

¹¹⁴ *Ibid.*, p. 99.

¹¹⁵ *Birch*, **2**, p. 128.

quicksilver lies upon the center of the section, the edges of the glass will be situated in a true horizontal plane'¹¹⁶. Hooke recorded this in *Animadversions*¹¹⁷, along with other levels as illustrated in figs. 25-27 of Fig. 5-9 ¹¹⁸.

Another device described in *Animadversions* was to ensure that quadrants 'being once adjusted, and set to the Objects, will continue to be so'¹¹⁹ — an equatorial in modern terminology. Target stars quickly move out of the field of view of a telescope, and the equatorial became an essential mechanism for observational astronomy in the seventeenth century. Indeed, Hevelius described a version of it to Oldenburg in 1668¹²⁰.

While Hevelius's equatorial was driven by a pendulum clock, Hooke used a 'Watch-work' with 'circular Pendulum' or a conical pendulum *p* in fig. 15 of Fig. 5-9 ¹²¹. The clockwork steadily rotated the axle *ab*, and this orientated the observing instrument via the socket illustrated in fig. 16 of Fig. 5-9.

In *Animadversions*, after the description of the equatorial, Hooke digressed onto his claim to priority over Huygens for the invention of the conical pendulum. Huygens had briefly discussed it in the fifth part of his *Horologium oscillatorium* (Paris, 1673)¹²². Hooke insisted that 'I invented it, and brought into use in the year 1665, and in the year 1666, I communicated it to the Royal Society'¹²³.

Hooke's joint also appeared in *Animadversions* (Fig. 5-9, fig. 22 therein). He said that he 'have made of this Joynt, for a universal Instrument for Dialling, for equalling of Time, for making the Hand of a Clock move in the Shadow of a Style, and for performing a multitude of other Mechanical Operations'¹²⁴. Further description of Hooke's joint is given, not in *Animadversions*, but in another Cutler Lecture *Helioscope* published two years later¹²⁵. It appeared in relation to an 'Instrument for describing all manner of *Dials* by the *Tangent projection*' (Fig. 5-10). He called the joint

¹¹⁶ *Ibid.*, p. 157. See also pp. 133 & 154.

¹¹⁷ *Gunther*, **8**, p. 101-102.

¹¹⁸ *Ibid.*, pp. 100-101. Hooke produced his levels at the meetings of the Society. For a survey of his talks, see note 51 of Bennett (1980).

¹¹⁹ *Ibid.*, p. 102.

¹²⁰ Hevelius to Oldenburg, 19 November 1668 (O.S.), *Oldenburg Corresp.*, **5**, pp. 181-192 (pp. 183, 187 & 190-192). As was explained in the letter, the device was his friend's idea.

¹²¹ *Gunther*, **8**, p. 104.

¹²² *Oeuvres*, **18**, pp. 73-368 (pp. 360-365).

¹²³ *Gunther*, **8**, pp. 105-106. This was the occasion on which Hooke showed a mechanical analogue of the movement of the planets.

¹²⁴ *Ibid.*, p. 109. He had already mentioned the device in 1667. See *Birch*, **2**, pp. 156 & 158-160. See also Bennett (1980), p. 37.

¹²⁵ *Gunther*, **8**, pp. 133ff.

mechanism here 'a Universal Joynt'¹²⁶ because of the 'Universality of this Contrivance, for resolving almost all *Spherical Questions*'¹²⁷.

Hooke concluded his *Animadversions* by asking 'To what purpose all this curiosity?'¹²⁸. He answered that 'it is of infinite value, to any that shall design to improve Geography, Astronomy, Navigation, Philosophy, Physics, &c ', that is, to take the exact refraction of the air from the horizon to the Zenith; to position the fixt stars; to find longitude and latitude of places; to examine the influence of the planets to the earth; to measure the angular or straight distance on the earth; to take the exact diameters of the celestial bodies; to take the level exactly.

Precision Astronomical Measurement by Hooke

Hooke's telescopic observations discussed so far were mainly performed within the framework of the Galilean Observation Paradigm: observations with long telescopes of the heavenly bodies inside the solar system. But in one of his Cutler Lectures, *An Attempt to Prove the Motion of the Earth* (London, 1674, hereafter, *Attempt*), we see another aspect of his research: the application of instruments to precision astronomical measurement. Hooke applied a telescopic sight with an eyepiece micrometer to the observation of the parallax of the fixed stars.

The detection of the parallax of the fixed stars was of critical importance in order to prove the motion of the earth. Wren, Hooke's predecessor in astronomy, also recognised its importance. He proposed methods for the necessary observations, and the Monument, his collaborative work with Hooke completed in 1677, was designed as a huge zenith scope¹²⁹. But Wren did not actually perform the observations¹³⁰. Hooke embarked on this frontline research topic himself toward the end of 1660s.

Hooke's research on the topic was first mentioned at the meeting of the Royal Society on 20 June 1668. The record reads:

'He [Hooke] undertook to make observations of the parallax of the earth's orb to seconds; he also to make observations with long telescopes without the use of a tube'¹³¹.

¹²⁶ *Ibid.*, p. 133.

¹²⁷ *Ibid.*, p. 138.

¹²⁸ *Ibid.*, pp. 111ff.

¹²⁹ Jardine (2002), pp. xi-xii; Jardine (2003), pp. 171-172.

¹³⁰ Sprat (1667), p. 315; Wren (1750), p. 198.

¹³¹ *Birch*, 2, p. 98.

The observation seems to have been delayed, because the following January Hooke 'was exhorted by the president to do [it] with all convenient speed'¹³². It was finally reported by the President on 22 October 1668 that:

'Mr. HOOK had erected a tube to try, whether he could observe to a second minute the passing of any fixed stars over the zenith, and thence find a parallax of the earth's orb, in order to determine the earth's motion'¹³³.

Hooke described the details of the observation in *Attempt*. He started the book as follows:

'Whether the Earth move or stand still hath been a Problem, that since *Copernicus* revived it, hath much exercised the Wits of our best modern Astronomers and Philosophers, amongst which not withstanding there hath not been any one who hath found out a certain manifestation either of the one or the other Doctrine'¹³⁴.

Tycho and Riccioli could not detect parallax, so they disagreed with Copernicus. But their observations with the unaided eye could not be 'experimentum crucis', the eye 'being unable to distinguish any angle less then a minute, and an observation requisite to determine this requiring a much greater exactness then to a minute'¹³⁵. Therefore Hooke resolved 'to assist my eyes with a very large and good Telescope, instead of the common sights, whereby I can with ease distinguish the parts of an object to Seconds'¹³⁶.

Hooke installed the whole observing instrument into his lodging, because a stable building obviated error from warp and stretch (Fig. 5-11, fig. 4 therein). The instrument was a long telescopic sight, with an object glass of thirty-six feet focal length set in a tube mounted through the roof. Its eyeglass was fixed in a firm support on the ground floor¹³⁷. He used a measuring instrument illustrated in fig. 7 of Fig. 5-11 ¹³⁸. It was made from a thin plate of brass. Within its aperture of about

¹³² *Ibid.*, p. 139.

¹³³ *Ibid.*, p. 315.

¹³⁴ *Gunther*, **8**, p.1.

¹³⁵ *Ibid.*, p. 4.

¹³⁶ *Ibid.*, p.9.

¹³⁷ *Ibid.*, pp. 17-18.

¹³⁸ *Ibid.*, pp. 19-20. This instrument may have been the one Hooke brought to the Royal Society meeting on 2 December 1669 (*Birch*, **2**, p. 409). In the same part of

nine inches, two thin hairs *ab* and *cd* crossed at *e* which was aimed on the zenith point. The distance to the target star from *e* was measured by the ruler *op* at the right with the help of the diagonal threads fastened at *u* and *m*.

Hooke began observation with the telescope on 6 July 1669¹³⁹. The target was the bright gamma star in the head of the Dragon constellation, which was near the zenith point of Gresham College¹⁴⁰. Stars near the zenith were preferable, because the light from them was free from atmospheric refraction¹⁴¹.

Hooke compared the data with that obtained on 20 October, and found a difference of more than 20 seconds¹⁴². He concluded that it was manifest:

‘that there is a sensible parallax or the Earths Orb to the fixt Star in the head of *Draco*, and consequently a confirmation of the *Copernican* System against the *Ptolemaick* and *Tichonick*¹⁴³.

But contemporary astronomers were sceptical about this¹⁴⁴. For example, Huygens wrote to Oldenburg on 5 May 1674 (O.S.) that ‘The Observation of Mr. Hook are very good, and of great consequence; but they must be continued’¹⁴⁵. William Molyneux (1656-1698), a good friend of Flamsteed, also suspended judgement on Hooke’s claim and wrote that ‘I leave the Reader to judge upon Perusal of his *Attempt*’ in his best-known book, the *Dioptrica nova* (London, 1692)¹⁴⁶. However in January 1694 when tabulating his observations, Flamsteed found an annual irregularity in the declination of the Polar Star, a phenomenon seemingly suggesting its parallax¹⁴⁷.

The irregular movement of the gamma star of the Dragon which Hooke had observed was confirmed by James Bradley (1693-1762), Savillian Professor of Astronomy and later Astronomer Royal, in 1725. Bradley began his observation with Samuel Molyneux (1689-1728), the son of William Molyneux, with a 24-foot zenith sector at Molyneux’s house. They soon found a displacement of the star, but to their

Animadversions, Hooke also mentioned the eyepiece micrometer with a sliding ruler described earlier (Fig. 4-5). See *Gunther*, 8, p. 20.

¹³⁹ *Ibid.*, p. 23.

¹⁴⁰ *Ibid.*, p. 13.

¹⁴¹ *Ibid.*, p. 15.

¹⁴² *Ibid.*, pp. 24-25.

¹⁴³ *Ibid.*, p. 25.

¹⁴⁴ Bennett (1982), p. 42; Chapman (1990), p. 87.

¹⁴⁵ *Oldenburg Corresp.*, 11, pp. 1-4 (pp. 1 & 3). An extract of the letter was published in *Phil. Trans.*, 9 (1974), no. 105, pp. 90-91.

¹⁴⁶ Molyneux (1692), p. 276. See also ‘William Molyneux’, *DSB*, 9, pp. 464-466.

¹⁴⁷ King (1955), pp. 110-111; MacPike (1937), p. 26.

astonishment this was in the opposite direction to that which parallax suggested. Bradley continued his observation, and finally discovered in 1728 that the displacement was caused by 'aberration of light'. It was a great discovery. Although it was not parallax, it nevertheless first confirmed the movement of the earth because the phenomenon was the combined effect of the velocity of light and the orbital motion of the earth¹⁴⁸.

It is true that Hooke failed to observe parallax. However, it should be remembered that Hooke was working at the leading edge of observational astronomy in his pursuit of precision astronomical measurement¹⁴⁹. The parallax of fixed stars was difficult to observe, and it was not finally confirmed until around 1840.

The Aerial Telescope

Hooke's long telescopic sight or zenith scope was a version of the 'aerial telescope', *i.e.*, long telescopes without the tube between the object and eyepiece lenses¹⁵⁰. Long telescopes were difficult to handle because of their weight, bending, and so on, and a way to avoid these difficulties was to omit the tube.

The best-known aerial telescope is probably that of Huygens's (Fig. 5-12). It appeared in *Astroscopia compendiaria* which Huygens published in 1684 at The Hague¹⁵¹. Henry King wrote that 'Christian Huygens was the first to discard the long wooden tubes of Hevelius'¹⁵². However, Hooke claimed his priority over Huygens at the meeting of the Royal Society on 25 June 1684¹⁵³. Though *Birch* did not print the details of his claim, his discourse was recorded in Hooke's manuscript lodged at the Royal Society¹⁵⁴. He argued that 'It is a long time since I acquainted this Society wth one Invention I had found some time ago of very long telescopes without the trouble of making or using tubes'¹⁵⁵. Indeed, we saw that Hooke used an aerial telescope as a

¹⁴⁸ King (1955), p. 112; *DSB*, 2, 'Bradley', pp. 387-389.

¹⁴⁹ It is indicative that only two works of Hooke were translated into Latin in his lifetime, and one of them was *Attempt (Conamen ad motum telluris probandum*, Oxford, 1679). Another was his treatise on capillary action. See Keynes (1960).

¹⁵⁰ Bendini (1967) had a different definition of the aerial telescope. He applied the term to long telescopes in general.

¹⁵¹ It is included in *Oeuvres*, 21, pp. 210-231.

¹⁵² King (1955), p. 54.

¹⁵³ *Birch*, 4, p. 308.

¹⁵⁴ Royal Society Classified Papers, vol. 20, no. 62, ff. 137r-140r. This manuscript has the heading 'This discourse was read June The 25th 1684', and a replication of Huygens's illustration (Fig. 5-12) is annexed to it (f. 140r). For further details of the manuscript description, see *Pugliese*, pp. 586-588.

¹⁵⁵ Royal Society Classified Papers, vol. 20, no. 62, f. 137r. In another manuscript Hooke went so far as to insist that Huygens described the aerial telescope 'above 20

zenith scope in 1669.

Moreover, in 28 February 1678, Hooke explained to the Royal Society his way 'of making use of glasses of any length without a tube'¹⁵⁶. His description here shows that the telescope was quite similar to that of Huygens's. However, Jonas Moore objected that it was 'only theory, and that it had never been practised or made use of, Mr HOOKE affirming, that he had done it, and found it convenient'¹⁵⁷. At the next meeting, Hooke again affirmed that 'he had tried M. HEVELIUS'S sixty feet glass without a tube'¹⁵⁸.

Nevertheless, the true story of the priority of the aerial telescope is complicated, and is difficult to pin down. As early as 1663, Huygens reported to Moray his success in mounting a 35-foot telescope without a tube¹⁵⁹. In his answer, Moray informed Huygens that Neile and Wren had considered using a telescope without a tube ten years previously to find the parallax of a certain star¹⁶⁰.

What is certain is that the idea of the aerial telescope was shared by several astronomers at that time, and that it served for astronomical observations including discoveries of two additional satellites of Saturn by Cassini in 1684¹⁶¹, the detection of parallax or aberration by Hooke and Bradley, and other observations.

The Establishment of Greenwich Observatory

Hooke published three Cutler Lectures on astronomy in the 1670s. However Gresham College, where the Lectures were held, was in decline after the Great Fire in 1666. The College building was used for the City Corporation and Exchange traders¹⁶². Lectures were suspended, and four years passed before the Gresham Trustees expressed their desire to reinstate them¹⁶³. Then, in 1672, the Lord Mayor was informed that Gresham professors neglected their duty to deliver lectures¹⁶⁴.

Years after I had used it here in *England* (*Philosophical Experiment*, p. 390).

¹⁵⁶ *Birch*, 3, pp. 388-389.

¹⁵⁷ *Ibid.*, p. 390.

¹⁵⁸ *Ibid.*, p. 392.

¹⁵⁹ Huygens à Moray, 18 novembre 1663 (N.S.), *Oeuvres*, 4, pp. 431-433 (p. 433); Bennett (1982), p. 41. Pugliese did not believe that the telescope mentioned in the letter was an aerial telescope in the true sense. He argued that the design 'simply called for omitting three of the planks of the tube, leaving a single board. See *Pugliese*, p. 587.

¹⁶⁰ Moray à Huygens, 29 novembre 1663 (N.S.), *Oeuvres*, 4, pp. 443-445 (pp. 444-445).

¹⁶¹ An Extract of *Journal des Sçavans* on Cassini's discovery was printed in *Phil. Trans.*, 16 (1686), no. 181, pp. 79-87. For the telescope used, see p. 83.

¹⁶² Adamson (1975), p. 231.

¹⁶³ *Ibid.*, p. 222.

¹⁶⁴ *Ibid.*, p. 223.

Some professors simply refused, and others absented themselves from the College¹⁶⁵. Even when the lectures were held, there was often no audience¹⁶⁶.

While the College, which supported mathematical sciences including astronomy, was destined to fade away in the seventeenth century¹⁶⁷, a new institution for astronomy was established as an independent and lasting organisation, *i.e.*, Greenwich Observatory.

King Charles II's Warrant of 22 June 1675 announced that the Observatory was to be built 'in order to the finding out of the longitude of places for perfecting navigation and astronomy'¹⁶⁸. The problem of longitude, or of developing a practicable way to determine longitude at sea, was of great importance in the mid-seventeenth century. Several methods were proposed for it, such as the computation of lunar distances from the sun or a fixed star, or observations of the eclipses of the satellites of Jupiter or of the moon's transit of the meridian, or the use of accurate clocks at sea¹⁶⁹.

In 1662, the Royal Society examined a method proposed by Henry Bond (c. 1600-1678), a navigational teacher, to use the variations of a magnetic needle¹⁷⁰. He also compiled elaborate tables of the variation and dip of a magnetic needle by 1673 for another method of finding longitude. Charles II appointed a committee to examine the second proposal¹⁷¹. Among the members of the committee were Moore, Brouncker, Moray, Pell, Wren and Hooke¹⁷².

Then a Frenchman, the Sieur de St. Pierre, who was a protégé of Charles II's mistress the Duchess of Portsmouth, announced that he had devised a lunar method. The King ordered the committee to give him the necessary data. In February 1675 a meeting was held, and Flamsteed censured the Sieur's proposal. Flamsteed was already known as a skilful self-taught astronomer, and was invited to the meeting as a guest by his patron Jonas Moore, Surveyor General of the Board of Ordnance. But the committee desired Flamsteed to fulfil the Sieur's demand. When Flamsteed's data was handed over, far from being satisfied the Frenchman complained that it was out of

¹⁶⁵ Adamson (1980), p. 23.

¹⁶⁶ Adamson (1978), p. 6, and see, for example, *Diary 1672-1680*, pp. 47 & 271-272.

¹⁶⁷ The Gresham Trustees rebuilt Gresham College in 1842, and it offered public lectures. See Hartley & Hinshelwood (1961), p. 134; [http://: www.gresham.ac.uk](http://www.gresham.ac.uk).

¹⁶⁸ Forbes (1675), p. 22.

¹⁶⁹ Merton (1970), p. 167; Bennett (1982), pp. 44-45 & 50-51; Sobel (1995); Andrews (1996).

¹⁷⁰ Hunter (1981), p. 95; *Birch*, 1, p. 104. For Henry Bond, see Taylor (1954), pp. 207-208.

¹⁷¹ Forbes (1975), p. 15.

¹⁷² *Ibid.*, pp. 17.

date¹⁷³.

The King heard about these exchanges, and was surprised to learn of uncertainty in the basic astronomical data required for navigation. He decided on 4 March 1675 to appoint Flamsteed with a salary of one hundred pounds per annum to:

‘apply himself with the most exact care and diligence to the rectifying the tables of the motions of the heavens, and places of the fixed stars, so as to find out the so much-desired longitude of places for the perfecting the art of navigation’¹⁷⁴.

Wren recommended building the observatory at Greenwich, and the foundations were laid on 10 August 1675. Flamsteed started his observation at the Observatory on 19 September 1676¹⁷⁵.

Flamsteed’s Precision Astronomical Observation

Flamsteed used a 7-foot sextant to compile his star catalogue *Historia Coelestis Britannica* (Fig. 5-13) ¹⁷⁶. He made about 20,000 observations with the sextant until 1689, when it was abandoned. It was designed and divided by Flamsteed, and constructed by Edward Sylvester and Thomas Tompion of London. Two telescopic sights were applied to the sextant, one fixed and one movable. The latter was driven by a perpetual screw instead of a clamp and tangent screw. Flamsteed originally ‘envisaged the earlier method but Hooke persuaded Moore the perpetual screw...should be adopted’¹⁷⁷. Henry King wrote that ‘There could be no better proof of the superiority of telescopic over plain sights than the work which Flamsteed accomplished with his 7-foot sextant’¹⁷⁸.

Among the instruments Flamsteed used at Greenwich Observatory was a mural quadrant Hooke made (Fig. 5-14). Moore was responsible for ensuring payment of Flamsteed’s salary. However, no money had been set aside for instruments for the Observatory. Therefore Moore accepted Hooke’s offer to provide a mural quadrant at low cost¹⁷⁹. It was a 10-foot quadrant designed by Hooke and made by Thomson of London. It was in place by July 1676, but Flamsteed had to spend much time trying

¹⁷³ *Ibid.*, pp. 18-19.

¹⁷⁴ *Ibid.*, pp. 19-20.

¹⁷⁵ *Ibid.*, pp. 22-23.

¹⁷⁶ Howse (1975), pp. 75-79.

¹⁷⁷ *Ibid.*, p. 76.

¹⁷⁸ King (1955), p. 107.

to make it work, before abandoning it as useless¹⁸⁰. On 16 July 1678, Flamsteed wrote to Moore that 'I have often tried to make Mr Hooke's wall Quadrant give mee altitudes and it has as often deceived mee and lost its rectification. I tore my hands by it and had like to have deprived Cuthbert [Denton] of his fingers'¹⁸¹.

Another Hooke-designed instrument at the Observatory was a screwed 3-foot quadrant made by Tompion in 1674¹⁸². It had been kept in the repository of the Royal Society at Gresham College. In January 1677, Moore persuaded the Council of the Society to lend it to the Observatory, against Hooke's opposition¹⁸³. Flamsteed used it primarily for the determination of time. He also discovered with it the variation of atmospheric refraction between morning and evening air¹⁸⁴. In October 1705, two years after Hooke's death, Flamsteed wrote to Newton as follows:

'Sr Jonas Moor borrowed Mr Hooks Quadrant of the R Society which being very well made I divided its limbe very exactly hung it conveniently & made use of it for 3 years together or More till upon ye decease of Sr Jonas, Mr Hook got it remanded'¹⁸⁵.

Moore died on 27 August 1679, and Hooke removed the quadrant from the Observatory lest the executors of Moore's estate regarded it as his property. Or this could have been Hooke's revenge on Moore for lending it to Flamsteed despite his opposition¹⁸⁶.

Flamsteed used not only telescopic sights but also eyepiece micrometers. When he came to Greenwich in 1675, he brought two refracting telescopes together with the micrometer Towneley made after Gascoigne's design¹⁸⁷. This had been presented to Flamsteed during his visit to London in the summer of 1671 by Moore, who in turn had received it from Richard Towneley¹⁸⁸. Thus, Flamsteed was an intensive user of instruments for precision astronomical measurement.

¹⁷⁹ Forbes (1975), p. 29.

¹⁸⁰ Howse (1975), pp. 17-19.

¹⁸¹ Flamsteed to Moore, 16 July 1678, Flamsteed (1995), pp. 643-646 (p. 645).

¹⁸² Howse (1975), pp. 111-112. Howse identified it as the one Hooke published in *Animadversions* (Fig. 5-6), even though the size differs. Pugliese confused the two quadrants discussed here. See *Pugliese*, pp. 578-579.

¹⁸³ Howse (1975), p. 111; *Birch*, 3, p. 331.

¹⁸⁴ Howse (1975), p. 111; Forbes (1975), pp. 36-37.

¹⁸⁵ Flamsteed to Newton, 25 October 1705, *Newton Corresp.*, 4, pp. 449-451 (p. 450). Its draft is published in Flamsteed (2002), pp.230-233.

¹⁸⁶ Howse (1975), p. 112; *Pugliese*, pp. 578-579.

¹⁸⁷ Howse (1975), p. 107.

¹⁸⁸ Forbes (1975), p. 27. Flamsteed could have used an eyepiece micrometer even before his meeting with Moore. See *DSB*, 5, p. 22.

His preference for these instruments was manifested in his attitude to Hevelius. We have seen Flamsteed's doubts about Hevelius's observations in his letter to Cassini in 1673 (see p.**). Flamsteed repeated his criticism of the plain sight in 1686. When Wallis defended Hevelius in *Philosophical Transaction* in 1685¹⁸⁹, Flamsteed wrote to Towneley as follows:

'You need not be concerned at Dr Wallis his account of Hevelius his booke hee is onely minding to gratifie his old friend. and speakes the better of him both because hee is sensible with the rest of the World of Mr Hookes intollerable boastes, as also by reason hee was never used to observations with great instruments and therefore understands not the advantages of telescope sights above plaine ones'.¹⁹⁰

Halley, who was to succeed Flamsteed as Astronomer Royal, was also critical of Hevelius's obstinate adherence to the plain sight, even though he made known in England the accuracy of Hevelius's observations. Halley had been convinced of the advantages of the telescopic sight over the plain sight. When the Hooke-Hevelius controversy resurfaced briefly in 1686 after the publication of Hevelius's *Annus climactericus*, Halley wrote to William Molyneux as follows:

'The Controversy between Mr. Hevelius and Mr. Hooke, as you very well observe does, as Hevelius manages the matter, affect all those observers that use Telescope [*sic*] sights, and myself in particular, and it is our common concern to vindicate the truth from the aspersion of an old peevish gentleman, who would not have it believed that it is possible to do better than he has done'¹⁹¹.

The Role of Hooke's Instruments in the History of Astronomy

The previous Chapter considered Hooke's astronomical observations within the framework of the Galilean Observation Paradigm. The present Chapter has covered Hooke's commitment to precision astronomical observations. Though preceding researches have not completely neglected Hooke's contribution to astronomy, they have failed to comprehend the true meaning of Hooke's research in this field.

¹⁸⁹ *Phil. Trans.*, **15** (1685), no. 178, pp. 1256-1265.

¹⁹⁰ Flamsteed to Towneley, 15 March 1686, Flamsteed (1997), pp. 280-282 (p. 281).

¹⁹¹ Halley to Molyneux, 27 March 1686, Halley (1932), pp. 57-60 (p. 60).

Indeed, since the Second World War analysis has been mainly in the context of optics, not astronomy as in present paper.

It is true that in the 1980s Hooke's astronomy was seen in a new light from the perspective of instrumentation. Bennett pointed out in 1980 that 'One of the most important aspects of the scientific work of Robert Hooke was his contribution to instrumentation', referring to Hooke's helioscopes, micrometers, telescopic sights, quadrants and so on¹⁹².

In 1989, two papers on Hooke's instrumentation appeared as the first two chapters of *Robert Hooke: New Studies*. The first chapter, entitled 'Hooke's Instruments for Astronomy and Navigation', was written by Bennett. This paper emphasised the importance of the telescopic sight and the eyepiece micrometer for the transformation of the telescope into 'a traditional astronomical instrument'¹⁹³. Bennett did not miss the value of these instruments.

However it is also the case that even Bennett failed to put the telescope and its attachments into the context of the astronomy of that time, even though he described the antagonism of Wren and Hooke to Hevelius. As we have seen, the telescope had already produced important astronomical discoveries in the early half of the seventeenth century, and it was well-established in Hooke's time. The author suggests that Bennett should have written that the telescope was transformed from a tool of the Galilean Observation Paradigm into one for precision astronomical measurement through the use of the telescopic sight and the eyepiece micrometer.

The second paper of *Robert Hooke: New Studies*, 'Robert Hooke and Practical Optics' by Simpson, shared the same difficulty. This paper gave us useful information on Hooke's collaboration with optical instrument makers such as Reeve and Cock. But the background against which the optical instruments were developed was not described. Simpson also discussed Hooke's helioscope. But he separated it from its context of the development of observational astronomy with long telescopes, so the full import of a method of folding the light path of telescopes seems to resolve into a simple technical improvement.

Hooke's instruments and astronomical observations are best understood when we regard him as an astronomer who stood just before the end of Galilean Observation Paradigm. He observed minute details of the planets with long telescopes. Long

¹⁹² Bennett (1980), p. 1 & pp. 39ff. As Bennett wrote in note 1, Westfall recognised the importance of Hooke's mechanical ingenuity for natural philosophy. However, in his papers on Hooke's optics, Westfall failed to regard Hooke in the context of astronomy.

¹⁹³ Bennett (1989), p. 21.

telescopes were difficult to handle, so he sought to contract them. Hooke also contributed to the transition to the next stage of observational astronomy, by promoting the use of instruments for precision astronomical measurement. Telescopic sights and eyepiece micrometers were crucial to the development or revival of positional astronomy. As Helden wrote, 'The watershed in positional astronomy was the debate between Hooke and Hevelius about the practicability of telescopic sights on measuring instruments'¹⁹⁴.

In his book on Wren in 1982, Bennett suggested an illuminating perspective. He wrote that 'Whether the use of telescopic sights led, in practice, to more accurate observations, was disputed between Hevelius and the English school'¹⁹⁵. Although he represented the English school by Hooke and Flamsteed, we may also include Wren and Halley in their camp. It is worthy of mention that they were rather like scientists in a modern sense, because they were affiliated to Gresham College and Greenwich Observatory, and were paid salaries by these public scientific organisations. In addition, Hooke was employed by the Royal Society as its Curator of Experiments. So we could interpret the dispute over telescopic sights as a confrontation between the amateur scientist Hevelius and English professional scientists.

¹⁹⁴ Helden (1974a), p. 55, note 93. See also Andrade (1950b), p. 456.

¹⁹⁵ Bennett (1982), p. 42.