William Gascoigne, Richard Towneley, and the micrometer

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The telescope screw micrometer was an instrument crucial for the advance of precision astronomy. Its original inventor, the Yorkshire astronomer William Gascoigne (c.1612–44), was killed in the English Civil War. His name is now known to historians of science around the world, but most of his papers were lost in the maelstrom of war and the few that survived later disappeared. His own micrometers and the modified versions made by Richard Towneley (1629–1707) have all been lost. This paper describes a project to create a faithful replica of Gascoigne's micrometer, based on surviving evidence. The aim was to utilize it in an optical system similar to that employed by Gascoigne and thus appreciate more readily the characteristics of the instrument and to ascertain its ease of use.

1. Introduction

As the French astronomer Adrien Auzout (1622–91) penned a letter to the Royal Society of London on 1666 December 28 (Old Style) he could not have imagined the consternation that it would cause. Nor could he have guessed that his action would almost certainly save from oblivion the work of a young astronomer from northern England who had suffered a violent death almost a quarter of a century earlier.

Full of enthusiasm, Auzout wanted to tell English scientific friends of his invention of the telescope screw micrometer: an entirely novel device that he (together with Jean Picard) had used to measure the angular diameter of the Sun, Moon, and planets. 'We can take diameters to seconds', he wrote, 'and we can be almost certain that we cannot be mistaken by more than 3 or 4 seconds... I can well assure you that the diameter of the Sun was hardly smaller at its apogee than 31′ 37″ or 40″.'[1]

1.1. *Prior claims*

When Richard Towneley (1629–1707), a wealthy Lancashire experimenter and patron of science, saw Auzout's letter in the *Philosophical Transactions* of the Royal Society, he was dismayed. Not only was he aware of the priority of the deceased Yorkshire astronomer William Gascoigne (c.1612–44) in relation to the ground-breaking instrument, he was actually in possession of three such screw micrometers made by Gascoigne a full 25 years earlier.

Towneley had probably been supplied with the *Transactions* by his friend and experimental collaborator, the physician Dr Henry Power FRS (1626–68) of New Hall, Elland, near Halifax. Power was already an admirer of Gascoigne. In his book *Experimental Philosophy* (1664) he had described the young astronomer as 'our famous and never to be forgotten Country-man, Master Gascoign of Midleton near Leeds, who was unfortunately slain in the Royal Service for His late Majesty; a Person he was of those strong Parts and Hopes, that not onely we, but the whole World of learning suffered in the loss of him.'[2]

Power persuaded Towneley to bring Gascoigne's invention to the attention of the Royal Society via a fellow physician, Dr William Croone (1633–84). Accordingly, on 1667 March 25, 'being particularly incouraged thereunto by Dr Power', Towneley wrote to Croone:[3]

> I am told I shall be look't upon as a great wronger of our Nation, should I not let the World know, that I have out of some scatter'd Papers and Letters, that formerly came to my hands of a Gentleman of these parts, one Mr. Gascoigne, found out, that before our late Civil Wars, he had not only devised an Instrument of as great a power as M. Auzout's, but had also for some Years made use of it, 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: which I the rather mention, because the French Astronomer esteems himself the first

that took any such Notice, as thereby to settle the Moons Parallax. For, our Countrey-man fully consider'd it before, and imparted it to an Acquaintance[4] of his, who thereupon proposed to him the Difficulties that would arise in the Calculation; with considerations upon the strange Niceties, necessary to give him a certainty of what he desired. The very Instrument he first made I have now by me, and two others more perfected by him; which doubtless he would have infinitely mended, had he not been slain unfortunately in his late Majesties Service. He had a Treatise of Opticks ready for the Press; but though I have used my utmost endeavour to retrieve it, yet I have in that point been totally unsuccessfull: But some loose Papers and Letters I have, particularly about this Instrument for taking of Angles, which was far from perfect. Nevertheless, I find it so much to exceed all others, that I have used my Endeavors to make it exact, and easily tractable; which above a Year since I effected to my own desire, by the help of an Ingenious and exact Watchmaker in these Parts…

I shall only say of it, That it is small, not exceeding in weight, nor much in bigness, an ordinary Pocket-Watch, exactly marking above 40000 Divisions in a Foot, by the help of two Indexes; the one shewing hundreds of Divisions, the other, Divisions of the hundred; every last division, in my small one, containing 1/10 of an inch; and that so precisely, that, as I use it, there goes above 2½ divisions to a Second. Yet I have taken Land-Angles several times to one Division.

A week later, to back this up, Power also wrote to the Society (maybe to Croone or Oldenburg):[5]

Worthy Sir

In some of yr last Phylosophycall Transactions it seems one Mons: Auzott hath auquainted ye world of his having found out an Instrumt to take ye Diameters of ye Planetts exactly by, and wherewh he can divide an inch into 25000 or 30000 parts.[6] I finding presently invited Mr Towneley to write to yuo of his screws and [wheel:] Instrumts (which he has to my knowledge some years agoe invented and made use of in ye like Case. wich I am Confident are as exact and good as Azotts can be, I [...?] signified something to you ere this about it, I pray give mee ye happinesse to continue this revived correspondence wt yuo and yuo will [sure] obliege

(worthy Sr)
yr most affectionate servant
Henrie Power

Wakefield, April ye 1st, 1667

By 1667 July 11 Robert Hooke reported to his Royal Society colleagues that Dr Croone 'had received from Richard Towneley, esq., Mr Gascoiyne's instrument for measuring the diameter of the stars [planets] with great exactnesse'.[7] The instrument was shown at a society meeting two weeks later and in due course, a description and drawing, made by Hooke, were included in the *Philosophical Transactions*.

1.2. *Examining the instrument*

Unfortunately, despite Hooke's drawing, we do not know how closely Towneley's micrometer resembled that of Gascoigne. Towneley claimed to have made the device more 'exact and easily tractable', but the precise extent of his modifications remains a mystery. Moreover, even the details of the Towneley variant itself are somewhat uncertain. Without a doubt it was a remarkably precise instrument for its time and consequently elicited the greatest admiration. The Royal Society members judged it to be 'a very ingenious and useful contrivance'.[8]

Screws had been used in astronomical instruments before Gascoigne's time, but these had usually been for slow-motion adjustment of settings or mountings such as in Tycho Brahe's steel sextant, c.1574,[9] and not for direct measurement or as a means of subdividing the units on a measuring scale.

A genuine screw micrometer, measuring fractions of turns and apparently capable of great precision, was made in 1609 by Christoph Trechsler (1546–1624) of Dresden, to a design by Lucas Brunn (c.1575–1624). Unfortunately, it was destroyed by bombing during World War II.[10] There is no indication that it was used for astronomical observations and no evidence that Gascoigne or Auzout were aware of it.

Gascoigne himself was the first person to make use of the Keplerian design of telescope – with its internal common focal point – to insert micrometer pointers into the optical path and thus initiate a major advance in precision astronomy.

1.3. *Use at Greenwich*

One of Towneley's micrometers – whether the one presented to the Royal Society or another example we do not know – was given by Sir Jonas Moore (1617–79) in the summer of 1670 to John Flamsteed (1646–1719) to test. This particular micrometer became part of the standard arsenal of the early Royal Greenwich Observatory and featured prominently in Francis Place's engravings (1676) of the Observatory's instruments.[11] Sadly, despite this impact, none of Towneley's micrometers, nor any of the earlier variants made by Gascoigne himself, have survived.

The present paper is the outcome of a project to recreate, as faithfully as possible, a Gascoigne–Towneley micrometer and to incorporate it in an optical system similar to that used by Gascoigne. In this way we hoped to understand its characteristics and assess its ease of use.

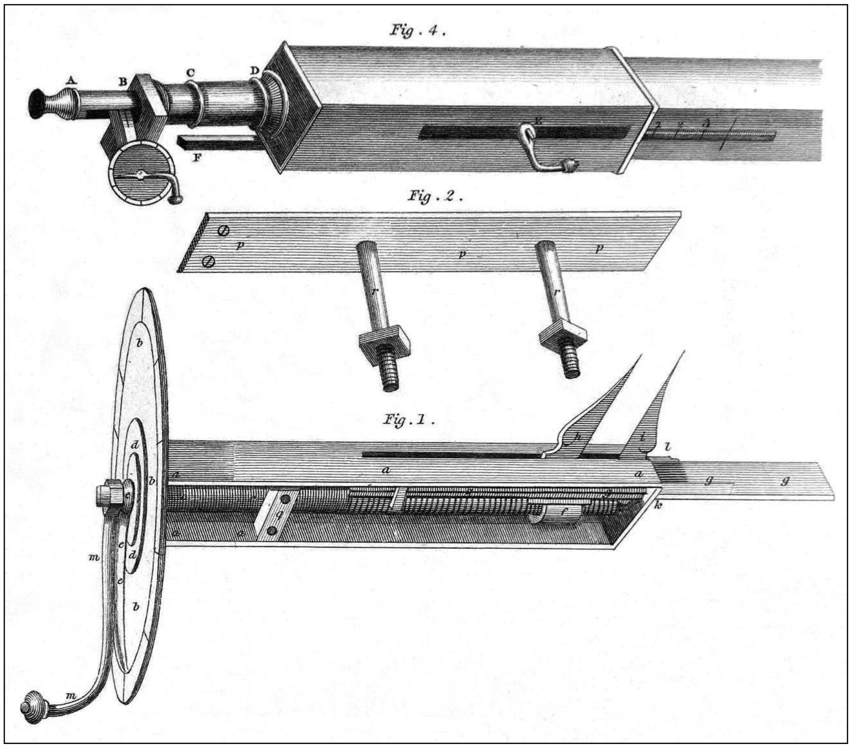


Fig. 1: *Robert Hooke's drawing of the Gascoigne–Towneley micrometer, as seen on Plate VI of the Philosophical Transactions of the Royal Society of London, Abridged, vol. 1, 1809. The original depiction was published in the Philosophical Transactions of 1667.*

2. Surviving drawings and descriptions

The letter that Towneley sent to the Royal Society in 1667 March revealing the existence of the micrometer did not say much about its design. Of its dimensions, he stated simply 'it is small, not exceeding in weight, nor much in bigness, an ordinary Pocket-Watch'. As concerns its precision: 'exactly marking above 40000 Divisions in a Foot'. For more detailed guidance on the specification of the micrometer we need to look to other sources.

2.1. *Flamsteed's Preface to the Historia Coelestis Britannica*
Although the Preface to Flamsteed's *magnum opus* does not describe the micrometer in any significant detail, it does at least go some way in clearing up one mystery: the relationship between Towneley's micrometer and the original one of William Gascoigne. Towneley said that with the help of a watchmaker he made improvements to Gascoigne's device. Flamsteed indicates one aspect of the improvements: 'Richard Towneley ... carried forward and completed his instrument (the micrometer) and made it perform with one screw, what on Gascoigne's instrument had required two.' [12]

Flamsteed was a friend of Towneley and the two made measurements together with the micrometer at the latter's house. Therefore, it is reasonably safe to trust his account.

2.2. *Hooke's description and sketch*
There is no record of the physical appearance of Gascoigne's original micrometer. The best we can do in attempting to create a replica is to concentrate on the device that was presented at the Royal Society meeting of 1667 July 25 incorporating Towneley's modifications. At a later meeting (1667 November 7) Robert Hooke was requested to produce a description and diagrams of this instrument, which were published in the *Philosophical Transactions*[13] (see Fig. 1, which is a slightly different version of Hooke's diagram that was published in the Abridged *Transactions* in 1809).

Unfortunately, Hooke's description is prolix and somewhat ambiguous. For example: 'The Screw hath that third of it, which is next the Plate, bigger than the other two Thirds of it, by at least as much as the depth of the small Screw made on it: The thread of the Screw of the bigger Third is as small, again, as that of the screw of the other two Thirds.'

The instrument depicted by Hooke is remarkably compact. The mechanism is contained in a brass box to which at one end is attached a circular brass plate 3 inches (76 mm) in diameter. This is the only useful dimension given by Hooke.

The circular brass plate carries a graduated scale with 100 divisions numbered in tens. Through the centre of the plate and passing through the length of the box is a carefully made single differential screw 'about the bigness of a Goose Quill', according to Hooke. The third of the screw's length nearest the graduated plate has fine threads, larger in diameter than the other two-thirds, which has coarse threads at exactly twice the pitch.

Hooke tells us that there are 60 turns of the coarser thread on the screw and that, corresponding to these, there are 60 divisions on the ruled bar. Although he states that the box and the plate are of brass, he does not specify the material of the other components.

When the handle at the end of the screw is turned, the screw rotates, making the nut holding the movable pointer (driven by the coarse screw) move along the box towards or away from the fixed pointer. As the nut moves, it carries along a ruled bar that indicates the pointer's displacement in relation to the fixed pointer in terms of the number of whole pitch-length increments. These increments are divided by hundredths using the dial hand against the scale on the circular plate.

The third of the screw with the finer threads drives a block which is screwed to the movable cover of the micrometer. Since this cover is to be attached to the telescope mounting, the movement of the block causes the whole micrometer assembly to move half the distance travelled by the movable pointer, but in the opposite direction. Thus, ingeniously, the pair of pointers maintain a position in the centre of the field of view, both equidistant from the optical axis of the telescope.

Further Hooke manuscript material, including sketches and notes about the micrometer, are contained in the *Royal Society Classified Papers* 2:13 f.3, but these add little to the paper published in the *Philosophical Transactions*.

2.3. *Flamsteed's correspondence*

In the summer of 1670, John Flamsteed had been presented with the Towneley micrometer by Sir Jonas Moore. Although Flamsteed was keen to start testing and using the instrument, there was a frustrating delay until he was able to obtain suitable lenses and a telescope tube. Eventually, he reported back to Moore in 1674 April.[14] By directly measuring the separation of the pointers, he had calculated that the screw turned 35.10 revolutions per inch of separation. Towneley, however, had found 34.65 revolutions per inch for a screw in his possession that was 'made in the same box' (a term then used for a threading die). Flamsteed therefore decided to adopt a more sophisticated approach to the calibration.

With the micrometer mounted in a telescope, he placed a target 72 inches (1.83 m) wide 10,903 inches (276.9 m) from the objective lens of the telescope. Then he adjusted the micrometer pointers to exactly encompass a crisp image of the target. For this tube length, 165.5 inches (4.20 m), he found that pointer separation corresponded to 38.33 turns of the screw. Simple geometry of similar triangles then dictated that the pointer separation was 1.0929 inches (27.76 mm), i.e. 35.07 revolutions per inch. Given that the scale on the circular plate had 100 subdivisions of a revolution, this meant the micrometer could divide an inch into 3507 parts.

In an earlier letter to Towneley on 1673 January 25 Flamsteed had noted that 'your old micrometer in which both the pointers moved, had 1,307 parts to an inch, the first new screws 3,465: your later 3,415'.[15] This suggests that the one in Flamsteed's possession was equivalent to the one with the first 'new' screws. Possibly the one with two moving pointers was a more direct descendant of the original Gascoigne model, which apparently had less precision.

On 1673 August 2 Flamsteed wrote to the mathematician James Gregory (1638–75) in response to a request for design information about the micrometer. Although the letter is very detailed, it is of limited help in constructing a replica – the diagram to which it refers does not survive, and Flamsteed was primarily describing an improved version that he himself had devised. The construction of his own design was long delayed, because 'our smith despaired of making mee such good screwes as Mr Townlys are'.[16]

2.4. *Towneley's manuscript description*

The Flamsteed papers in the archive of the Royal Greenwich Observatory (now held at the library of the University of Cambridge) contain a hitherto unpublished manuscript description of the micrometer by Richard Towneley himself.[17] This is in Latin and has been transcribed and translated for this project by Dr Roger Ceragioli (University of Arizona); it appears on the following two pages. The description coincides with the Hooke version in the main, but does appear to indicate that the micrometer screw was made of steel ('chalybeus') rather than brass.

Another important design matter covered by Towneley's paper, but not Hooke's, concerns the manner of attaching the movable cover to the micrometer box so that the required lateral sliding is possible. Towneley reveals that:

> There is also a steel peg (omitted from the illustration)[18] in plate *p,p* implanted near its middle on a perpendicular, which crossing through the box itself is inserted into a slot in the forward plate, in such a way that it always holds the box in contact with the plate *p,p* such that, however, it allows the box to move right and left, according as it is extended in either direction by the screw *c,c* and the nut *f*.

A further interesting detail given by Towneley is that

> pointer *e,e* (like the pointer of a portable clock) is moveable, such that when the other pointers, *h* and *i*, are in contact it can be moved at will to the beginning of the numbers inscribed on the circumference of plate *b,b*.

3. Selected specification

It is clear from the above appraisal of the surviving sources (Hooke, Flamsteed, and Towneley) that the micrometer was an evolving instrument with several variants designed by Towneley and Flamsteed. The

Description of the micrometer by Richard Towneley[17], transcribed and translated by Roger Ceragioli

Towneliani Micrometri Authoris Ipsius Descriptio

[*f.72r*]

Prima Pars hujus Instrumenti notata Literis a,a,a,a,a,a,
fig: j. ae[note 1] Exhibet formam ac magnitudinem Thecae aeneae,
cujus Extremorum alteri adferruminatur ejusdem me:
:talli Laminae[2] Orbicularis b,b,b, huius Centro inseritur
Extremitas altera Cochleae cc: (quam ab omni recipro
:cationis motu Cohibet illa alia Lamina d:d: majori
imposita) Altera vero Extremitas Cochleae incumbit
Puncto k: Index g[3]: (ob rationem mox dicendam) in
:teriori Ipsius Thecae parti affigitur ad b[4]; ità ut per
Rimam a,a, emineat, ut in figurâ cernitur. Dicta
autem cochlea matricem sive cochleam feminam
habet f: Cui Regula, sive ex aera lamina lata, et longa
g,g,g,g: adhaeret, quae intra Thecam acta, circa ipsius
medium ad a, debitae magnitudinis foramini inseri
:tur, per quod hâc, et illâc libere movetur Circumactâ
cochlea, et in situ superiori Thecae parti paralello[5]
semper Continetur. Huic Regulae affigitur index alter
h. Ipsius Thecae lateri a,a,a; Perpendicularis, seu
quod idem est, alteri Indici j, (Quotiès cochlea Circum:
agitur) Paralellus[6] semper existat, sed etiam ad dis:
:tantias inter utrumque indicem designandus.[7] Hoc
autem facit, ope alterius Indiculi l; Ipius Thecae
extremitati affixi, qui Clarius in anteriori facie
Instrumenti Cernitur, cum hic in Diagrammate pos:
terior[8] sese tantum Videndum Exhibeat. Index autẽ[9]
hic Tertius[10] l; Varias inter priores indices h et j;
distantias designat, beneficio notarum illic ipsi Re:
gulae g,g,g, incisarum; ubi post singulas Cochleae Circum:
volutiones per manubrium m; factas sese sistit Ipsa
Indiculi, l; Extremitas.

[*f.72v*]

Hinc autem fit ut Indiculus; suo motu ipsarum circum:
:volutionum numerum notet; Index vero Quartus
e,e,e: singulas Circumvolutiones in Centum Partes
aequales dividat in quot divisa est Circumferentia
Orbicularis Laminae b,b.

Hâc ratione Indices h; et i; tantum ab Invicem
dimovere opera Cochleae possumus quantum ipsa Coch:
leae Rimaeque a,a: longitudo patitur; Quinetiam
Opera Indicum l; et e,e: in Partes minutissimas hanc
distantiam dividere, at vero si (Supposito quod in:
dices h, et i; primo contigui sint, et Centro tubi Applicat:)[11]
Cochleam Circumagas ut eosdem ab Invicem ad
Angulum dimetiendum, dimoveas, Adhuc tantum In:
:dex h: (Immoto Indice j:) ad latus Tubi Sinistrorum[12]
dimovebitur, cum tamen, ut ritè haec operatio insti:
tuatur, oporteat utramq$_3$[13] Indicem aequaliter a Cen:
:tro tubi distare; huic autem Incommodo sequenti
Inventione obviam Itum est.

Eidem axi Calybeo,[14] Cui incisa est Cochlea, (de quâ prius)
et Aci[15] in:equitat matrix f; cum affixo Indice h)
alia etiam Cochlea Circumciditur e,e, in eandem,
in quam prior, partem Contorta, sed cujus helices
dimidio minores sunt helicibus Prioribus: haec autem
Cochlea minor matricem q. habet, et haec matrix
duobus Clavis Laminae p,p,p, fig^{ae} 2^{dae},[16] quae pars Thecae
posterior est ipsi Telescopio alijs Clavis affixa, prout
fig^{a}[17] Quarta Exhibetur) Hoc autem Artificio fit, ut
Circumactis unâ ambabus cochleis per manubriũ[18]
m, per dimidium illius Spatij per quod Sinistrorsum
Index h fertur; dextrorsum feratur ope minoris
Cochleae. Integra Theca a,a,a; (Excepta posteriori
parte p,p,p, quae Telescopio adhaeret;) atque hinc acci
:dit ut aequali Intervallo uterq$_3$[19] Index h, et j; a Centro tubi distet,
Quod in hac re unicè necessarium est.

[*f.73r*]

Est autem (qui in Schemate omittitur; Paxillus ferreus La:
:minae p,p, propè medium ad Perpendiculum infixus qui per
Thecam ipsam transiens rimulae[20] in anteriori Lamina eo
modo inseritur, ut ipsam Thecam[21] Contiguam semper tene
at Laminae pp, Ità tamen ut illi <co>piam[22] dextrorsum, sinis:
:trorsumque movendi faciat, prout in alter:utram Partem
a cochlea, c,c, et matrice f. dirigitur.

Deniq$_3$[23] Index e,e, (instar Indicis horologij portatilis) mo
bilis est, ità ut Contiguis illis alijs indicibus, h, et j, ad nu:
merorum Initium in Circumferentiâ Laminae b,b, descrip
:torum pro libitu moveri possit. Hic autem Index e,e, cen
:tessimas partes illarum divisionum Commonstrat; Quae
:aciei[24] Regulae g,g: Impressae, ab Indiculo l, dinumerantur.
Hae sunt hujus Instrumenti partes utcunque descriptae,
ad quas ritè elimandas requiritur Artificis faberrimi
Industria, p^{e}sertim[25] ad cochleas efformandas, quarum
Helices et exactâ Proportione, et ea fieri ex subtilitate
Oportet, ut Oculorum aciem pene[26]: effugiant; hinc enim
in numerosissimas partes distantiae dividuntur. Haec au
:tem omnia in instrumento descripto adeò accuratè facta
Inveniuntur ut illius ope Pollex qui pars pedis Anglicanj
12ma[27] est, in partes 3415 dividatur, pes Anglicanus
ad Gallicum se habet, ut numerus quindenanus ad nu:
-merum 16.

Notes

1. i.e. *figurae i.ae*, that is, *figurae primae*.
2. An error for *Lamina*.
3. Error for *i*?
4. Error for *k*?
5. i.e. *parallelo*.
6. i.e. *parallelus*.
7. Meaning uncertain: *designandas?*
8. Reading uncertain.
9. i.e. *autem.*
10. Reading uncertain.
11. Perhaps *se Applicent*, or *Applicentur*?
12. An error for *Sinistrorsum*.
13. i.e. *utramque.*
14. i.e. *Chalybeo.*
15. A corrupt word of unknown significance.
16. i.e. *figurae secundae*.
17. i.e. *figura*.
18. i.e. *manubrium.*
19. i.e. *uterque.*
20. Reading uncertain: lacuna.
21. Reading uncertain: lacuna.
22. Reading uncertain: lacuna.
23. i.e. *Denique.*
24. Reading uncertain: *faciei*?
25. i.e. *praesertim*.
26. i.e. *paene.*
27. i.e. *duodecima*.

Description of the micrometer by Richard Towneley[17], transcribed and translated by Roger Ceragioli

The Author's Own Description of the Townelian Micrometer

[*f.72r*]

The first part of this instrument, marked with the letters *a,a,a,a,a,a,* (Figure 1) shows the shape and size of the brass box, to one of whose ends is soldered a circular plate *b,b,b* made of the same metal. In the center of this is inserted one end of the screw *c,c* (which is prevented from all oscillatory motion by plate *d,d*, fitted to the larger plate). The other end of the screw rests on point *k*. Index *g* (for a reason to be told shortly) is attached to the inner part of the box itself near *b*, [note 1] such that it projects through the slot *a,a*, as is seen in the figure. Moreover, the said screw has a nut or female screw *f*, to which is connected the ruler *g,g,g,g*, a plate of brass long and wide, which when driven inside the box to about its middle at *a*, is inserted into an orifice of appropriate size, through which it freely passes this way and that, when the screw is rotated. The ruler is kept always in upper position parallel to the direction of the box. To this ruler is affixed a pointer *h*, which is perpendicular to the side *a,a,a* of the box itself – or what is the same thing – it always remains parallel to the other pointer *i* (no matter how many times the screw is rotated) for the purpose as well of marking out the distances between either pointer.[2] It does this by aid of another small pointer *l*, attached to the end of the box, which is seen more clearly on the front face of the instrument, though here in the diagram the rear face alone is shown for viewing. Moreover, this third pointer *l* indicates the different distances between the previous pointers *h* and *i* by benefit of marks engraved on the ruler *g,g,g*, where the end of the small pointer *l* stops after individual revolutions of the screw, made by the handle *m*.

[*f.72v*]

Hence it comes about that the small pointer by its movement marks the number of revolutions themselves. A fourth pointer *e,e,e* divides individual revolutions into 100 equal parts, which is the number into which the circumference of the circular plate *b,b* is divided.

In this way, we can separate the pointers *h* and *i* apart from each other by action of the screw, just as far as the length of the screw and slot *a,a* allows. Indeed, by action of the pointers *l* and *e,e*, we can divide this distance into very minute parts. But if (supposing that pointers *h* and *i* are initially in contact, and are applied to the center of the tube[3]) you should rotate the screw so as to separate the pointers one from the other to measure an angle, at present only pointer *h* (pointer *i* being immobile) will move to the left toward the side of the tube, when however it should be the case for the operation to be properly performed, that each pointer stand equally apart from the center of the tube. This inconvenience is met by the following invention.

On the same steel axle, on which the screw is cut (about which we spoke earlier), and[4] the nut *f* rides (with affixed pointer *h*), another screw *e,e*[5] is also cut, turned in the same direction as the preceding, but with threads smaller by one-half than the preceding threads. This lesser screw has a nut at *q*, and this nut is attached to the telescope by means of the two bolts in plate *p,p,p* (Fig. 2) – which plate forms the rear side of the box – as is shown in Figure 4. By means of this artifice it comes about that when both screws are revolved together by means of the handle *m*, the entire box *a,a,a* (except the rearward part *p,p,p*, which is fixed to the telescope) is carried to the right by means of the lesser screw through one-half as much space as the pointer *h* is carried to the left. And hence it occurs that both pointers *h* and *i* are separated from the center of the tube by equal intervals. This is uniquely necessary in the present matter.

[*f.73r*]

There is also an iron peg (omitted from the illustration) in plate *p,p* implanted near its middle on a perpendicular, which crossing through the box itself is inserted into a slot in the forward plate, in such a way that it always holds the box in contact with the plate *p,p* such that, however, it allows the box to move right and left, according as it is guided in either direction by the screw *c,c* and nut *f*.

Finally, pointer *e,e* (like the pointer of a portable clock) is moveable, such that when the other pointers, *h* and *i*, are in contact it can be moved at will to the beginning of the numbers inscribed on the circumference of plate *b,b*. Moreover, this pointer *e,e* displays hundredth parts of those divisions that are impressed on the face of ruler *g,g* and are counted by the small pointer *l*. These are the parts of this instrument, however well described. To finish them off duly requires the diligence of a very skilled artisan, especially the cutting of the screws, whose threads ought to be made both with exact proportion and such subtlety that they nearly escape the eyes' scrutiny. For thus distances are divided into the most numerous parts. Moreover, in the instrument described all these things are found so accurately made that by its aid, a thumb[6] (which is the 12th part of an English foot) is divided into 3415 parts – the English foot being to the French as 15:16.

Transcription and translation by Dr Roger C. Ceragioli, University of Arizona, Tucson, USA

Notes

1. The meaning of this sentence is obscure. Perhaps *g* is in error for *i*, and *b* for *k*, so that the correct meaning is "Pointer *i*…is attached to…the box at *k*."
2. The meaning of the Latin text is uncertain and appears to contain an error.
3. The meaning of the Latin text is uncertain.
4. The Latin text at this point contains an unknown word *Aci* which appears to be a mistake of some kind. It is omitted from the translation.
5. Presumably a mistake for *c,c*.
6. i.e. an inch.

specification adopted for this project, drawing on these sources, is intended to produce a working replica close in appearance to the original one presented to the Royal Society in 1667 July.

When modelling the micrometer with computer-aided design software it became apparent that the description and sketch were lacking in details. These missing details were carefully designed into the replica consistent with early 17th-century tools, materials, and methods. When designing the replica, some values in Hooke's description could not be satisfied without conflict. Therefore, the replica has some differences in the number of divisions on the scale and thread count on the screw.

Below are the key components and dimensions (with inches in parentheses to assist comparison with the original):

- Box, brass: 89 × 12 × 17 mm (3.5 × 0.475 × 0.7 inch)
- Dial, brass: 76 × 1.6 mm (3.0 given by Hooke × 0.063 inch)
- Handle, brass: 3.6 to 3.3 mm + 0.76 mm diameter knob (0.14 to 0.13 inch, + 0.3)
- Scale, brass: 89 × 6 × 1.6 mm (3.5 × 0.227 × 0.062 inch)
- Hand, brass: 2.8 to 0.8 mm (0.11 to 0.03 inch)
- Spring plate, brass: 25 × 0.6 mm (1.0 × 0.022 inch)
- Screw, steel: Fine section 23 mm (0.9) long, 4.8 mm (0.1875) diameter (60 threads per inch); coarse section 47 mm (1.85) long, 4 mm (0.156) diameter (30 threads per inch).

4. Fabrication

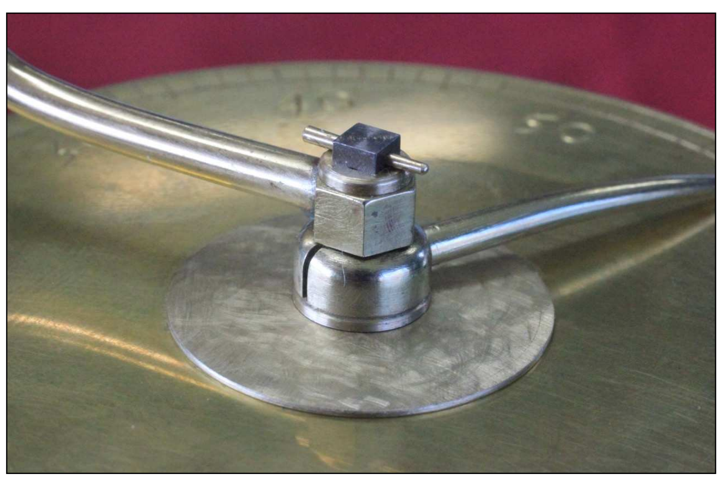
Box: The three-sided box was machined out of a piece of solid brass. The method in the 17th century would most likely have been to use several individual pieces soldered together, or a casting. Although Hooke mentions the dial being 'screwed' on to the box, Towneley says that it was soldered on. On our replica we soldered the dial, as it was easier and safer given the thin cross-section of the box.

Fig. 2: *Cutaway computer visualization of the replica micrometer.*

Dial, hand, and handle: The engraving of the dial division lines and the end-scale division lines were scribed using machine tools with a rotary table and the linear motion of a milling machine. The font used for the numbers is styled so as to be similar to those found on scientific instruments of the period. The numbers were hand-sketched about 75 mm high on paper, and the outline was followed by hand using the stylus of a pantograph, which reduced the numbers to the correct height on the dial and scale. This was used only to lay out and lightly mark the numbers. Using these marks as a guide, the actual engraving was done manually with a hand-engraving tool, either pushed or lightly tapped with a small hammer.

The crank handle was machined and bent, and the hub was soldered on. The same method was used for the dial hand.

Fig. 3a and 3b: *Dial plate, spring plate, and dial pointer hub fixing detail. Compression of the spring plate provides friction which prevents unwanted rotation of the screw and also gives additional end-shake protection.*



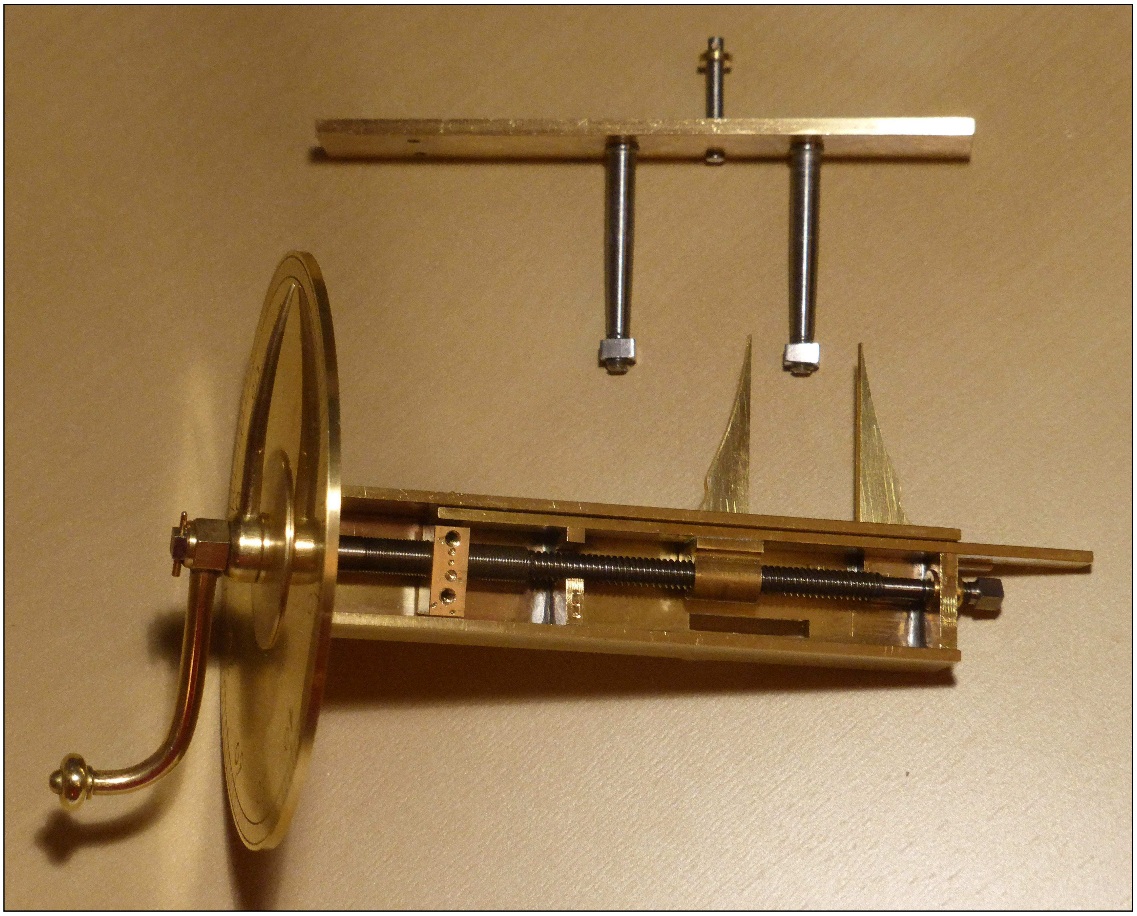


Fig. 4: *Our finished replica of the Gascoigne–Towneley micrometer. Note the slot in the back of the box and the single steel peg on the cover, which engages with it. This feature described by Towneley cannot be seen on the Hooke engraving.*

There is a lack of detail in Hooke's sketch and description regarding the handle and the dial hand. In our replica the handle and hand are arranged so that the handle is keyed to the screw shaft on a square and a smaller-diameter boss extends towards the dial spring plate (see Fig. 3a). A cross-drilled hole and a tapered pin, commonly used in watchmaking, is used to secure the handle (Fig. 3b) and also the sliding pin (Fig. 4). This smaller diameter cylindrical section is where the hand is located. The inside of the hand hub is slightly smaller in diameter than the boss on the handle and is split to permit it to rotate with friction on the handle boss. This allows setting zero on the dial when the pointers touch.

Screw: Only the coarse thread of the screw, the one that moves the pointer, is critical to the accuracy of the micrometer. The fine-pitch thread is used only to keep the position of the pointer pair in roughly the centre of the field of view. It is not critical that this 'centring' screw section be accurately machined or exactly half the pitch of the coarse screw. The screw was made from carbon steel, 12L14. The iron/steel of the early 17th century was likely different, but similar in appearance and strength.

Screw accuracy: It is natural to wonder how accurate screws of this period were. Up to the time of Gascoigne's micrometer, there was no need for accuracy in screws as they were primarily used as fasteners. So how accurate were the Gascoigne and Towneley screws?

We will never know. The demand of the instrument only requires the screw to be consistent in pitch along its length. No other descriptions of accuracy apply, although a watchmaker of the day would likely have beautifully crafted the screw (and the entire instrument) to a high standard consistent with practices dictated by the watchmaking trade.

There are references to screw-threading by master screw lathes as early as 1480, represented by a rough sketch in the *Mittelalterliche Hausbuch*. This lathe looks as though it was intended for wood. Not until many years after Gascoigne's work with micrometers were thread-cutting lathes commonly available. It seems unlikely that Gascoigne or anyone in the area would have had

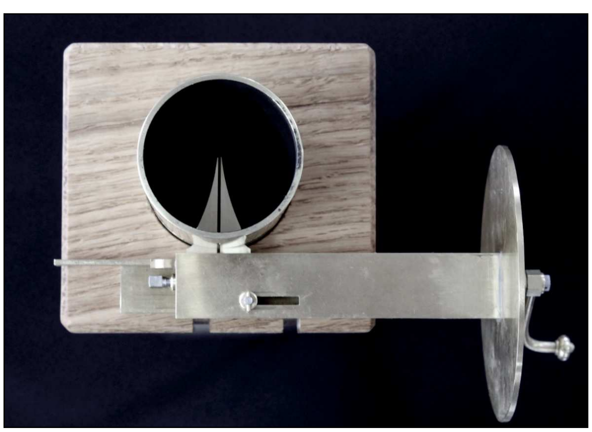
Fig. 5: *The telescope mounting method. The two steel threaded pegs riveted to the micrometer brass cover fit into oversize slots in the square oak block, which provides the ability to adjust the position of the micrometer in the light path.*

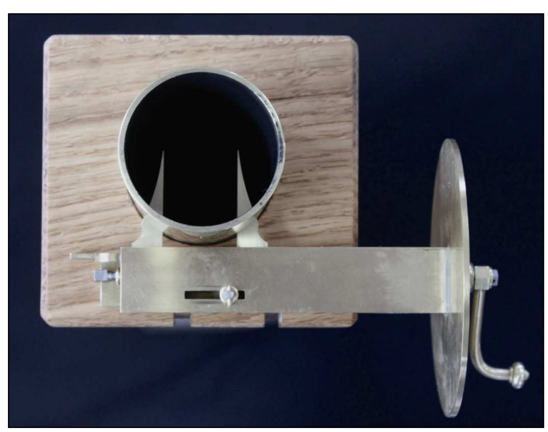
access to a screw-cutting lathe. Flamsteed mentioned to Moore (see above) that Towneley used a screw box (very similar to threading dies today) for cutting threads.

It is conceivable that Gascoigne's and Towneley's screws were the most accurate screws made at that time, possibly by a significant margin. Flamsteed wrote to Towneley on 1676 December 11: 'I am confident that yours [i.e. the micrometers] are much better made than mine especially if made by Hum: Adamsons Father, for Humphrey has not made the screws of mine so good as I would have them and I can not at this distance from London procure him to follow my directions ...' [19]

Spring plate: Hooke noted 'a small springing plate *dd* on the outside, so adapted to the plate that it is not in the least subject to shake. The other end of the screw is, by another little screw (whose small point fills the centre or hole made in the end of the longer screw for this purpose) rendered so fixed and steady in the box, that there appears not the least danger of shaking'.

Fig. 6a (left): *View of the pointers almost closed with the eyepiece removed.*
Fig. 6b (right): *View with the pointers open. Note the capture pin sliding in the slot.*





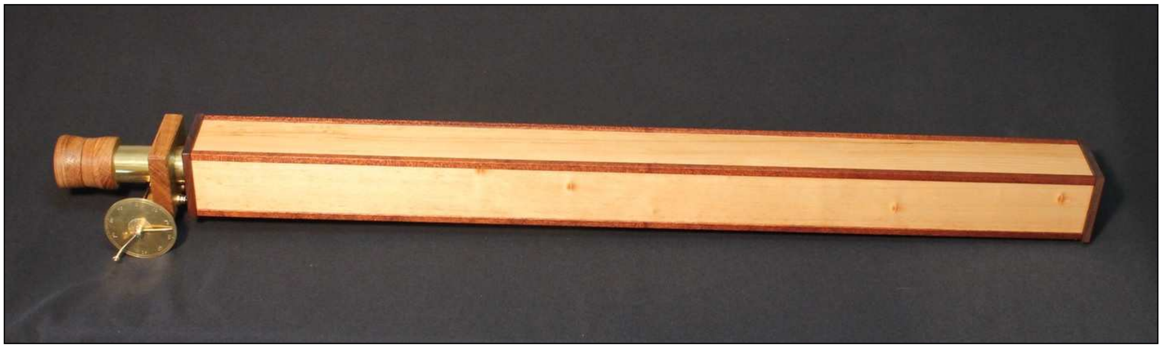


Fig. 7: *The tube assembly. The 970 mm case of the telescope is approximately the same length as that used by Gascoigne.*

Experience with our replica suggests that the end screw is sufficient to prevent end shake and keep the main screw aligned. After the micrometer has been worn-in, the weight of the handle and hand is enough to make it rotate when not desired. Probably the main purpose of the spring plate is to add friction to prevent this inadvertent movement.

Pointers, nut, and scale: In our replica micrometer the two brass pointers have been made removable using dovetail tabs that slip into dovetail sockets, one at the fixed end and one in the movable nut. The pointers are quite delicate and would probably have been replaceable. Removable pointers are also suggested by Hooke's sketch of alternative bow-shaped pointers with a stretched thread instead of Towneley's straight edge. Also, when designing the replica, we discovered that if the pointer on the nut/scale assembly was fixed permanently, it was not possible to assemble the micrometer.

The movable nut is soldered to the scale, which also functions as a guide, stabilizing the nut and pointer and constraining it to move with only one degree of freedom. The scale is engraved with 30 divisions per inch and is numbered each tenth of an inch. Each rotation of the handle moves the pointer 1/30 of an inch, which results in the replica being able to read 3000 parts per inch.

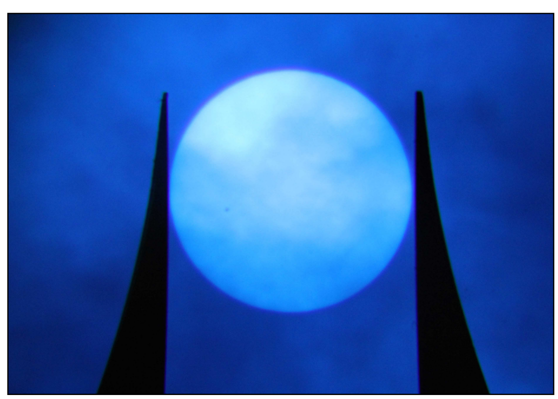
Accuracy of components: When constructing a device that has translating parts controlled by a screw and nut, it is very important that all the parts be aligned and parallel. The screw, dial plate, sliding scale with coarse nut, and the sliding base plate with its fine thread nut, have to be very accurately aligned with respect to each other. Excessive misalignment will result in binding and wear.

Alignment of these parts, while not exceedingly difficult, does require careful manufacture. One might think that precision machines are required, but in the case of one-off instruments the fabricator can make each part to fit during assembly. This is how watchmakers achieve accuracies beyond their measuring ability. The micrometer replicas were also made in this way, which means that the parts are not interchangeable.

Calibration: Calibration was simple and accurate for Gascoigne. A surveyor's chain or similar measuring device can be used to measure a distance and then a piece of that chain, or an accurate scale, can be observed with the telescope and measured with the

Fig. 8: *An eagle nest in some snags 1200 metres away (image inverted).*

Fig. 9: *The Sun's disk, viewed through the replica telescope and micrometer.*



micrometer. Simple trigonometry will then give the resulting angle. Increased accuracy is obtained by calibrating at several locations along the screw to average out any residual errors along its length.

Tube assembly: There is little information to indicate the design of Gascoigne's telescope tube assembly. Typical of that period were small round tubes, probably paper covered with vellum, and square-section tubes of wood construction as shown in Hooke's drawing (Fig. 1). For building a telescope to test our replica micrometer we chose the latter form: a small square-section wooden tube, a wood plate to hold the objective, and a wooden plate and block to hold the brass tube housing the micrometer.

Gascoigne used a Keplerian telescope with a plano-convex objective and a biconvex eyepiece. Although surviving correspondence does not reveal the dimensions or properties of his own lenses, a reasonable approximation can be inferred from the advice he gave in a letter of 1641 January 25 to William Crabtree, who was hoping to build a similar telescope.[20] The eyepiece should be about two inches (50 mm) in diameter, 0.3 inches (7.6 mm) thick, and – based on the type of glass he was using – would have a focal length of about 2.6 inches (66 mm).

Based on his observation of 1640 December 24, reported in the same letter, his objective (of unspecified diameter) had a focal length of 44.95 inches (1.14 m).[21] Assuming that both lenses were possibly stopped down to one inch (25 mm), this would have resulted in a system of about $f/45$ and a magnification of ×17.28.

We obtained surplus commercial lenses for our replica. The objective used was 30 mm diameter and 1000 mm focal length and was stopped down to 25 mm by the cell. The eyepiece was 42 mm diameter with a focal length of 60 mm. This resulted in the replica telescope being $f/39.37$ with a magnification of ×16.68.

The method of mounting the micrometer was similar to the Hooke diagram in that the micrometer was mounted on a wooden block in which a brass tube was fixed. This brass tube was slotted to accept the two pointers protruding from the box of the micrometer. The eye lens was mounted in a turned wooden holder, which was friction-fitted to the brass tube.

The engagement of this turned eyepiece was used to set the focus of the eye lens with the micrometer pointers. The pointers were focused against the objective by sliding the brass tube in and out of the wood tailpiece. The brass tube could also be rotated to align the pointers as desired for observing.

5. Testing and measuring

The procedure used for testing and calibrating the replica micrometer was similar to that used by Flamsteed, i.e. measuring objects of known size and distance with the micrometer mounted in a telescope. The first method used was a piece of wood with divisions every 100 mm, which was placed on a pole at a distance of 108.1 m. This introduced a slight error, about 1%, because of the need to refocus on an object closer than infinity (Flamsteed's calibration at a distance of 277 metres would have been essentially perfect). With the pointers closed, the hand on the dial was set to zero and the divisions were measured.

To calibrate at a much longer distance, a Wild T1 theodolite was used to measure the angular separation on several objects 600 metres distant and the results averaged. This particular telescope–micrometer system was calibrated to 1.73 arc seconds per dial division. The pointers were always moved from the open position towards a closed position, which removes backlash in the system.

Figure 8 is an image of an eagle's nest through the eyepiece of the replica telescope with the micrometer pointers across the field of view. The image shows off-axis colour, but the image in the centre is quite good. Figure 9 is an image of the Sun through some clouds. The micrometer recorded the separation of the pointers as 1140 divisions, resulting in an angular diameter of 1955″, which closely agrees with the true value of 1948″ on that date.

6. Significance in astronomical history

There is a temptation to assume that Adrien Auzout had to reinvent the telescope micrometer in 1666 because Gascoigne's prior invention had been lost, and that therefore the latter sadly had no significant role in the history of astronomy. This, however, would be a serious misreading of what happened before and especially after Auzout's reinvention.

Even as Auzout's letter of 1666 December 28 was being read out at a meeting of the Royal Society there were murmurings from attendees such as Christopher Wren and Robert Hooke that such a device was 'a thing not at all new among the English'.[22]

It is entirely possible that Gascoigne's idea, which had been communicated during his lifetime to William Oughtred, Kenelm Digby, and others, had spread further afield. It was certainly being fine-tuned and utilized by Towneley. More importantly, the use to which Gascoigne's instrument was put after the Auzout letter truly earned it an important, if forgotten, place in the annals of astronomy.

In 1672 November, Flamsteed and Towneley used the micrometer at Towneley Hall to make observations of the parallax of Mars, which allowed them to deduce a solar parallax of 10″ (about 14% too large).[23]

Flamsteed was bowled over by the capabilities of the Gascoigne–Towneley micrometer and ensured that one was installed at the Royal Greenwich Observatory when he became the first Astronomer Royal. Thus, it played a key role in collecting the invaluable data for which the Observatory is renowned. In the autumn of 1676, Francis Place made a series of engravings showing the Greenwich instruments, and took care to depict that very micrometer affixed to one of the telescopes.[24]

In the 1680s, Isaac Newton, demonstrating the universality of his theory of gravitation in the *Principia*, did so by considering the movements of Jupiter's satellites as revealed by successive measurements taken by Towneley and Flamsteed with the Gascoigne–Towneley micrometer.[25]

Thus, despite the early death of its original inventor in the maelstrom of civil war, Gascoigne's micrometer, as developed by Richard Towneley, survived to play a significant role in the advent of precision astronomy and the progress of science.

Acknowledgements

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