A COMMENTARY

ON

JESSE RAMSDEN'S

CIRCULAR DIVIDING ENGINE

BY

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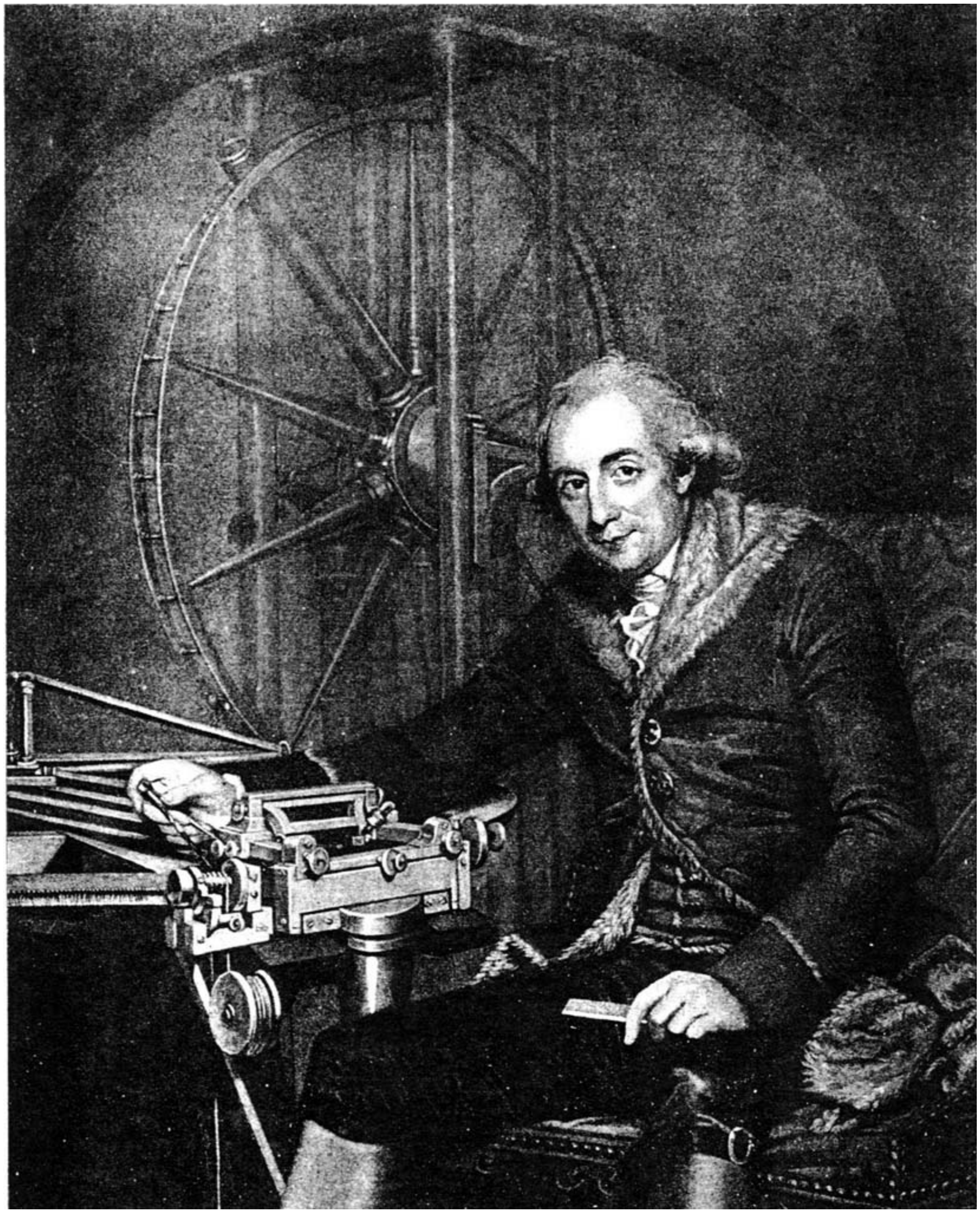

Frontispiece

Jesse Ramsden and his circular dividing engine

A COMMENTARY ON JESSE RAMSDEN'S CIRCULAR DIVIDING ENGINE.

INTRODUCTION

Thanks perhaps largely to Dava Sobel and the various incarnations of her book, *Longitude*[1], the works of John Harrison, if not his name, spring readily to the minds of many members of the general public. Few people, however, even those with a keen interest in navigation, will have heard of Jesse Ramsden, a more than equal genius of the eighteenth century. Ramsden was acknowledged to be the greatest instrument maker of his period and perhaps of all time, but it is in connection with the sextant that he deserves to be better remembered amongst navigators.

By about the middle of the eighteenth century it had been realised that finding one's longitude depended on knowing the local time, either by means of an accurate clock that would keep time at sea, or by using the passage of the moon across the background of the stars or sun as a celestial clock. Both methods required a means of measuring angular altitudes of heavenly bodies or the angle between the moon and the bodies. At this time, the scales of hand-held instruments for doing so were divided laboriously by hand, and as it was not a very accurate process, the instruments were necessarily large, typically of about 400 mm (15 inches) radius. Ramsden's second dividing engine changed the whole process to one in which the accuracy built into a machine was transferred to the instrument being divided and at a rate far faster than before. Its advent allowed sextants to be made more accurate, smaller, lighter and of more rigid materials. Ramsden also appears to have been responsible for the tapered index arm bearing, which remained standard for nearly all sextants made thereafter.

In the words of an unnamed author in the *European Magazine and London Review*[2] for February 1789: "*The reflecting quadrant, or sextant of Hadley, so much used by English seamen, appeared to Mr Ramsden the most useful instrument of its kind; but it was at this time extremely imperfect. The essential parts of it had not a sufficient degree of solidity; the friction at the centre was too great, and in general the alidada*[3] *might be moved several minutes without any change in the position of the mirror; the divisions were commonly very inaccurate, and Mr Ramsden found that Abbé de la Caille*[4] *did not exceed the truth in estimating at five minutes*[5] *the error to which an observer was liable in taking the distance between the moon and a star; an error capable of producing a mistake of fifty leagues in the longitude.*"

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[1] Sobel, D. *Longitude*. New York, 1995

[2] European Magazine and London Review. February 1789, XV; 92 - 96

[3] "index arm" is the term now more commonly used for the alidade. The word comes to us via Latin from the Arabic word "al idada", meaning "straight rule".

[4] Nicolas Louis de Lacaille. 1713 - 1762

[5] Navigators will not need to be told this, but other may need to know that a minute (strictly an arcminute) is one sixtieth of a degree.

The author is probably referring to the period around 1768, when Ramsden, having served his time as an apprentice and as a journeyman, opened his own shop in the Haymarket, London. By 1789, Ramsden had made 983 sextants and had "*now brought them to such a degree of perfection as to warrant it* (the error) *not more than six seconds*[6] *in a sextant of fifteen inches*." At this time, Ramsden was aged 58 years and the whole tone of the article suggests that the account is the result of an extended and contemporary interview with its subject, by someone well-informed about instrument making.

Ramsden appeared to have had a passion for accuracy and in about 1766 completed the construction of his first circular dividing engine which, while it was better than all others then existing, did not meet his exacting standards in that it had errors of up to three arcseconds[7]. A further eight years of development resulted in his second version, completed by 25 June 1774, when the minutes of the Board of Longitude reported a communication from him[8]. An error of less than one second of an arc was claimed for his second engine. Neville Maskelyne, the Astronomer Royal, and Dr Shepherd, the Plumian Professor of Astronomy at Cambridge, reported favourably on it[9], and a decision was made to make an award to Ramsden upon several conditions.

The award, totalling £615, was made up of £300 "…*as a Reward for the Improvements made by him in the Art of dividing Instruments by means of the said Dividing Engine, and for Discovering the same;..*" and the other £315 for making over the ownership of the engine to the Commissioners of Longitude. However, he was allowed to retain the engine for his own use provided that he also divided octants and sextants brought to him by other instrument makers, at a cost of three shillings for an octant and six shillings for a sextant. He was also required to give "*a full and complete written Explanation and Description (accompanied by proper drawings)..of the Engine*…" as well as instructing up to ten other instrument makers for up to two years on how to make and use not only the engine, but also the lathe which was used to make the worm screw of the engine. We shall see that the latter and the lathe used to cut it was almost as an important innovation as the engine itself.

Five hundred copies of his account were printed [10], and unlike, say, that of Harrison and his chronometer, it was on the whole a model of clarity. Most subsequent writers seem to have been satisfied simply to adopt Ramsden's own words, but I hope by adding a commentary I may be able to add an additional dimension to them for those with little or no familiarity with the details of instruments, instrument making and engineering drawings. I will follow

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[6] There are sixty arcseconds in an arcminute, so that an error of one second in a full circle represents about 1 part in 1.25 million.

[7] It was disposed of and found its way to Bochard de Saron and thence to the Musée des Arts et Metiers in Paris.

[8] Board of Longitude Confirmed Minutes for 25th June 1774.

[9] Ibid. Confirmed Minutes for 1 June 1775

[10] Ramsden, J. D*escription of an Engine for dividing mathematical instruments*. London, 1777.

Ramsden's order of description, but unlike Ramsden, I will be able to insert figures close to the text which refers to them, and embellish them where necessary. Anita McConnell has written a very full account of his life and works[11]. I do not intend to rival her comprehensive book, but rather give a different perspective to one small but, for the history of science and navigation, extremely important part of Ramsden's achievements.

The illustrations in what follows will usually stand enlargement to at least 200 percent and allow appreciation of the fine engravings. Thomas Malton, the elder (1726 – 1801), a noted architectural draughtsman, did the drawings and they were engraved by James Basire (1730 – 1802). I have often digitally enhanced them or made some additions to them to illustrate a point in the commentary. The photographs are of an engine in the Science Museum, London. It is a very close copy, almost certainly constructed by John Troughton. The original Ramsden engine is in the Smithsonian Institution. Ramsden's successors sold it to Messrs Knox and Shain of Philadelphia, who in turn sold it to Henry Morton in about 1880. Morton donated it to the Smithsonian in 1890.

George Huxtable and Clive Sutherland helped me by reading various drafts, posing penetrating questions and making comments. As this commentary is not well adapted to being published in book or journal form, Frank Reed kindly agreed to my suggestion that it could be archived on NavList, to be found at http://www.fer3.com/arc/.

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[11] McConnell, A. *Jesse Ramsden*. Farnham, 2007.

PART I

TITLE PAGE

a :*Commissioners of Longitude*
This was the short title for “Commissioners for the Discovery of the Longitude at Sea”, set up in 1714 to encourage innovation by offering prizes of up to £20,000 for a method that would determine the longitude to within 30 nautical miles.

b, c : *Strand; Tower Hill*
Ramsden’s home was in Piccadilly. He had been apprenticed to Mr Burton in the Strand, and Tower Hill was also a centre of instrument making in the eighteenth century. Haymarket, where he had his shop, is midway between the Strand and Piccadilly Circus and, with the exception of Tower, all are within minutes walk of each other.

d : *Price five shillings*
There were twenty shillings in a pound sterling. Fifteen to twenty pounds a year was a low wage for an independent artisan in C18 and forty pounds a year was needed to keep a family in reasonable comfort[12]. Seven shillings would buy a stout pair of shoes[13]. A sextant by Ramsden sold for about £13.

PREFACE, first page

a : *Engine…*
This was what we would nowadays call a screw cutting lathe.

b : *Endless Screw,…*
A worm or worm screw, but some of the terminology lived on in the US BuShips sextant Mark II, which was sometimes annotated “E.T.S.” (endless tangent screw).

c *: intelligent workman…*
This is rather hopeful. To produce even the lathe for cutting the “endless screw” would be challenging in a modern jobbing engineer’s workshop, equipped with modern machine tools. The dividing engine would pose even more of a challenge.

d : *Octants…*
More commonly called a quadrant, as it could measure up to ninety degrees, though the arc subtended only 45 degrees or one eighth of a circle, hence “octant”.

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[12] http://www.oldbaileyonline.org/static/Coinage.jsp
[13] http://footguards.tripod.com/08HISTORY/08_costofliving.htm

PREFACE second page

e : *shall be brought…*
Only the best and largest makers, like Edward Troughton and Samuel Rhee, could make their own engine. Most of the others got specialists like Ramsden to divide their sextants.

f : *brass Sextant*…
Octants very often made of wood and had only ivory arcs, and it is these that were commonly engraved with the divider's mark. Brass or silver arcs belonged to the better instruments, usually sextants, and were presumably harder on the scriber than was ivory. As well as the arc being thirty percent longer, sextants were often more finely divided, to read to twenty or even ten seconds.

g : *Nonius*…
Nonius is an alternative term for what we now mostly call the vernier scale. In an instrument measuring to 30 seconds, twenty divisions on the vernier would cover 39 on the main scale or 19.5 degrees of scale. The literature seems to be silent on how the divisions were made at the correct distance apart. I give my best guess on page 29.

TEXT, page 1

a : *Bell-metal…*
A hard bronze with a very high tin content, typically around 20 percent tin and 80 percent copper. Unlike brass, it is relatively easy to make good castings from it, but it is much harder and more difficult to machine with the tools available to Ramsden.

b : *mahogany…*
At this time the wood would have been *Swietenia mahagoni* (Cuban mahogany) or *Swietenia macrophylla* (Honduras mahogany). Mahogany has a straight grain, is strong, rot-resistant and easy to work.

c : *three legs…*
Time and again, Ramsden shows his appreciation of kinematic design, in which redundancy of support is avoided, in order to reduce stress and consequent distortion of parts.

d : *conical friction pully…*
More accurately, these were conical *anti*-friction pulleys.Only three were used to avoid redundancy. The mounting is shown in Figure 1 below (see also Figure 2

on page 9). Note the conical end of the outboard journal, which receives thrust and also ensures centring. The top of the roller projects through a clearance slot in the base board.

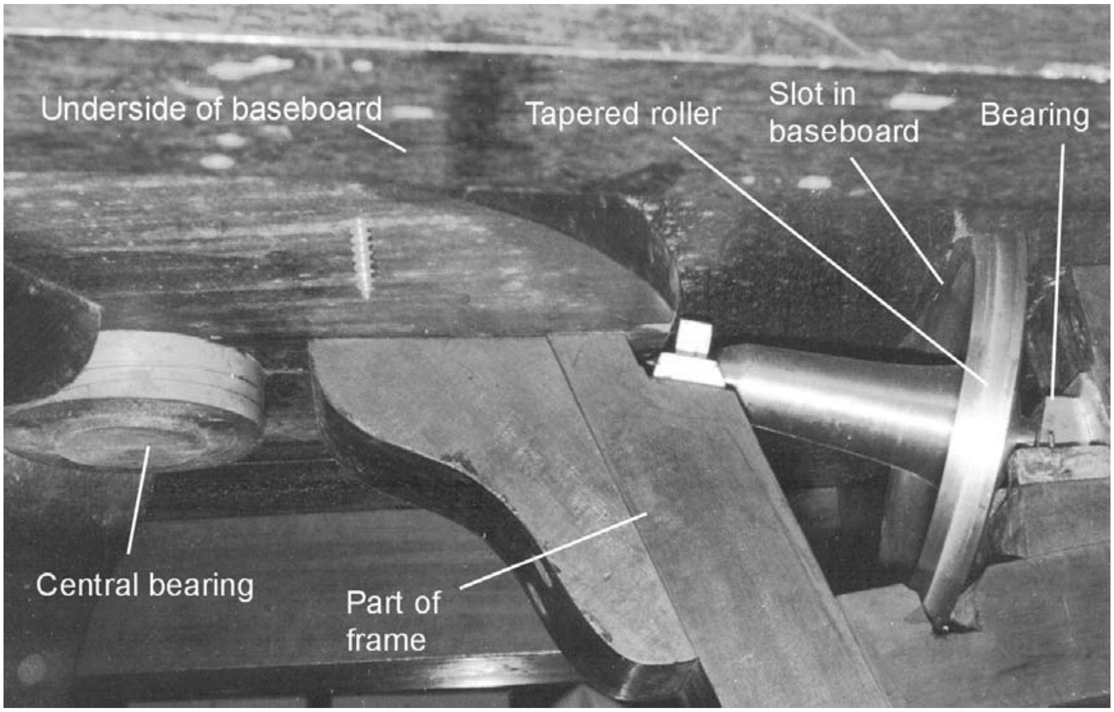

Figure 1

e : In both the texts I have examined, this line is unclear. It reads : *..bell-metal centre under it turns in a socket…*

f : *2160 teeth..*
2160/360 = 6, so the crests of adjacent teeth subtended ten arcminutes at the centre (60/6).

g : *endless Screw…*
Worm (see note b, page 6, above)

h : *Ten Seconds*
One full turn of the worm rotates the wheel through ten minutes, or 600 arc seconds. 600/60 = 10, so each division at the circle of brass represents 10 seconds

TEXT page 2

a and b : *Arbors of tempered steel…*
Steel is first hardened by heating to red heat and then cooling rapidly. In this state it is very hard, but brittle. It is tempered by further heat treatments to make it less hard, but tougher. An arbor is shown as “d” in Figure 2 below. It is tapered to ensure positive centring in the upper end of the arbor in the centre of the wheel, “D”. This part is also tapered to fit a matching taper in the wheel, thus ensuring positive location at the true centre of the wheel. The lower end of the wheel arbor is tapered, to fit a matching short tapered hole in a socket, “Z”, on the stand and its lower end can be seen in Figure 1 (p. 8) at centre left. This serves only to locate the wheel, while the tapered roller, “W” carries the load via the heavy circular rib “B”.

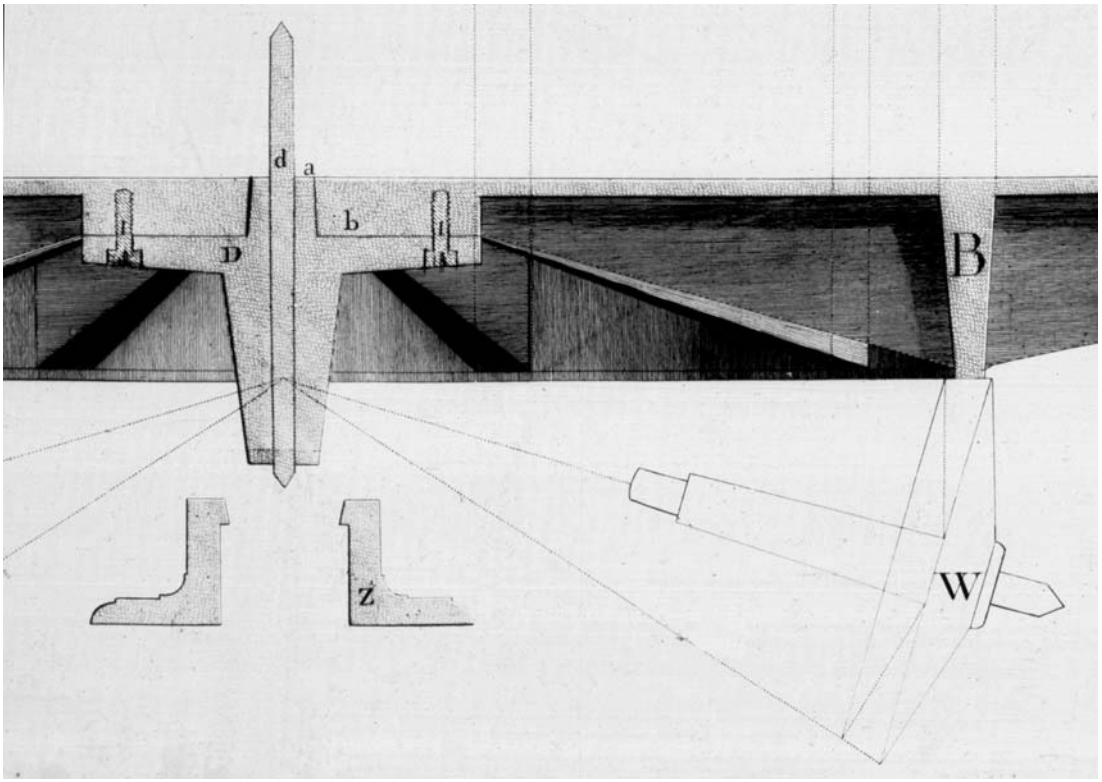

Figure 2

c : *angular notch…*
We would probably call this a “vee notch”, shown as “b” in Figure 3 below (see also Figure 18, p 24 below).

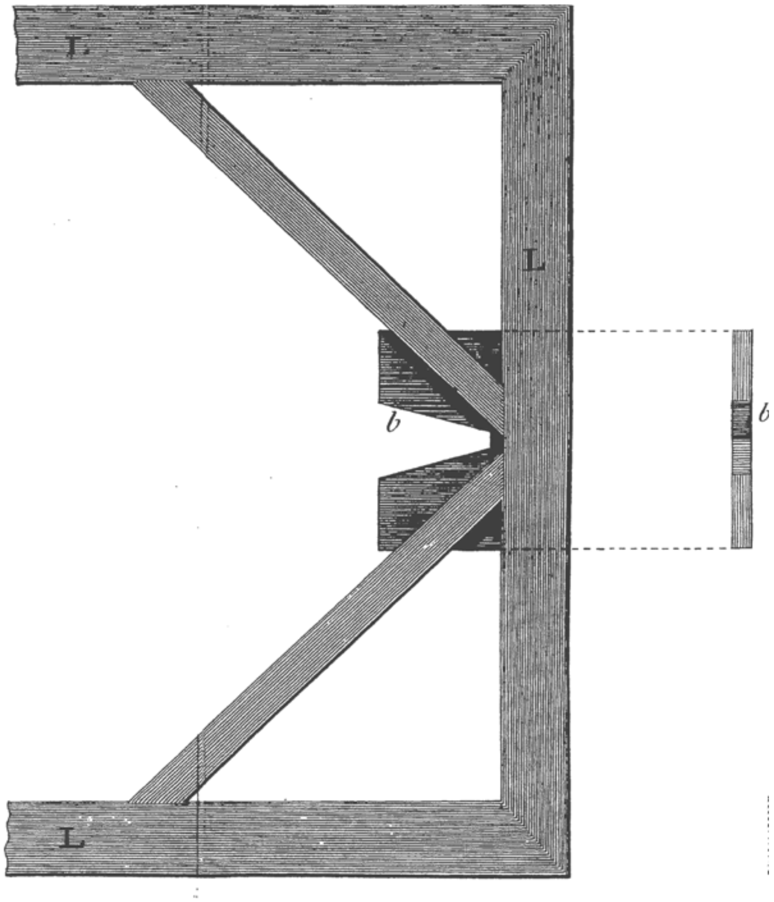

Figure 3

d : *shake…*
Free movement, usually unwanted, between two parts.

e : *lateral shake…*
Lateral shake or side to side movement of the tracer would of course be fatal to the accuracy of divisions made by the engine.

TEXT page 3

a : *cutting by means of a straight edge…*
Formerly, a blade called a dividing knife was used to make the divisions, by aligning a straight edge with the centre and a mark made at the periphery of the circle. It was difficult both to locate the centre of an existing hole and to guide the knife accurately despite hard spots in the metal being scribed.

b : *any eccentricity of the Wheel and its Arbor would not produce any error in the dividing;*
I think this must mean that the effect of eccentricity of the wheel upon *its* arbor was eliminated. The screw frame rotates around the same true dead centre[14] that mounts the instrument being divided.

c : i.e. the axis of the worm is always tangential to the wheel.

d : *line ΠΛ...*
These are the capital Greek letters *pi* and *lambda*. The account of Ramsden's life in the Appendix will show that he was no uneducated mechanic. The letters are hard to see, so I have circled them in the following drawing (Figure 4):

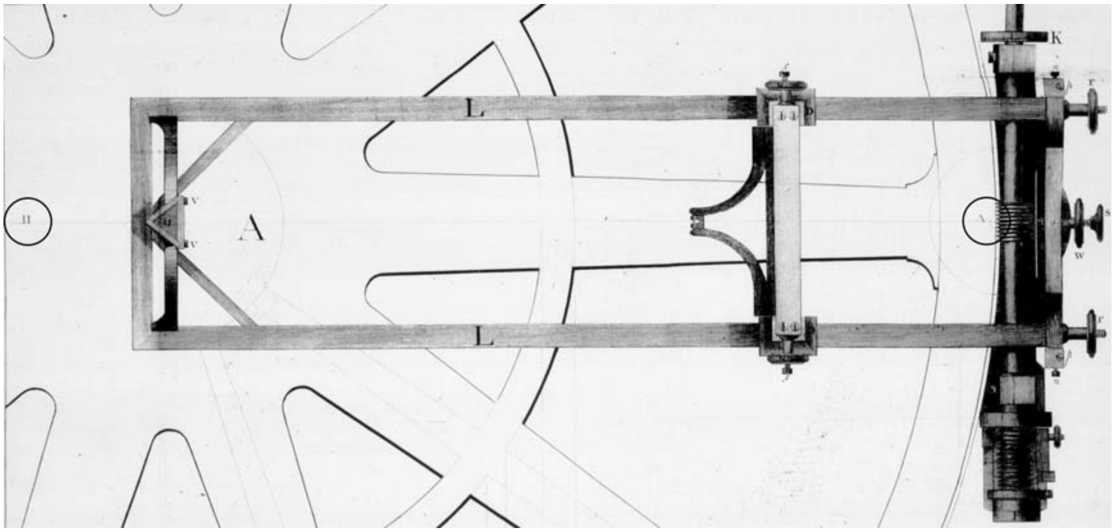

Figure 4

e : *45 inches…*
About 1145 mm.

f : *24 inches in diameter and 3 deep:*
About 610 mm and 76 mm. By scaling the drawing, it is possible to see that the radial ribs ("edge bars") were about 38 mm or 1.5 inches thick, so it was a very substantial casting.

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[14] dead centre: the work revolves around a dead centre, while the work rotates with a live centre. Any eccentricity of the latter or irregularity of its bearing is reproduced upon the work.

TEXT page 4

a : *fine brass…*
Fine brass would be less likely to have hard or tough spots in it and be easier to work.

b : *were well riveted…*
Figure 5, below, of part of the scale of a C18 sextant, shows to the right of the number 50 the appearance of a screw head after riveting and finishing flush with the surface.

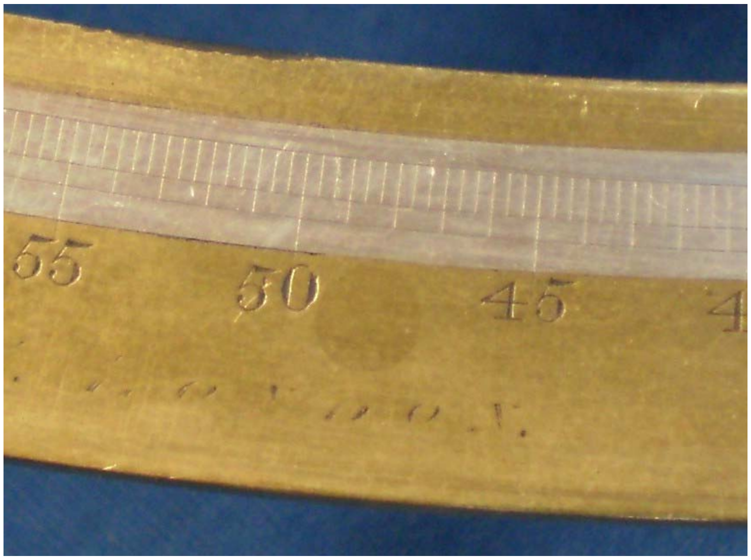

Figure 5

c : *true and flat in the lath,*
The lathe may be used not only for generating cylinders and cones, but also for generating flat surfaces truly square to the axis of rotation. This is done by traversing the cutting tool in a straight line at right angles to the axis of rotation of the work piece ("facing"). The face of the wheel was presumably first faced flat on the lathe before being turned over so that the remaining surfaces could be turned and faced.

d : These surfaces are shown arrowed in blue in Figure 6, below. Turning them all without demounting the wheel from the lathe would ensure concentricity and squareness. Note that the periphery was turned concave, to increase the area of contact of the worm.

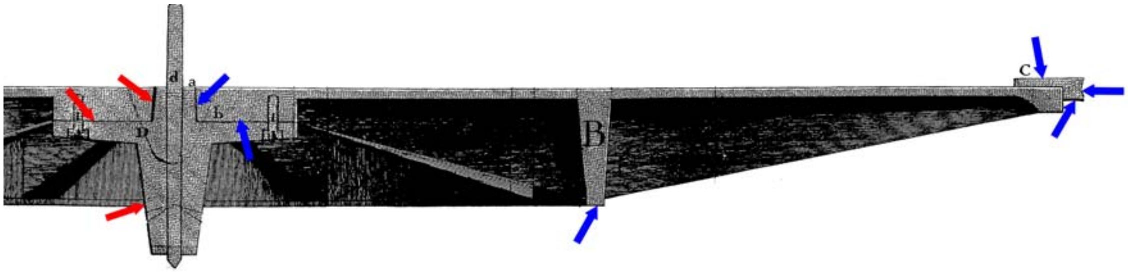

Figure 6

e : *turned very true on an arbor…*
This is a way of ensuring that a hole in a workpiece and its outer surfaces are concentric. A close fitting-shaft or arbor is made by turning it between centres. The workpiece is then mounted on the arbor and the outside turned to size and shape between the same centres. The external surfaces turned in this way are shown arrowed in red in Figure 6, above.

f : *perpendicular to the plane of the wheel;*
If the surface is turned flat (as opposed to conical) it follows that it must be square to the axis of rotation. With modifications, this is a method still used to generate a high-precision cylindrical square, whose base is at right angles to its side.

g : It is not clear why he made this bearing tapered when a plain cylinder would have served just as well. Perhaps having discovered the self-centring properties of tapered bearings, he had got into a habit of always using them.

TEXT page 5

a : *three conical friction pullies W,*
Although the heavily built and well-triangulated frame is well shown in the perspective general arrangement drawing (Plate 1), only a glimpse of the conical anti-friction pulley, labelled W, is possible. It is shown ghosted in Figure 2 on page 9 above. Ramsden shows that he appreciates the geometry of a tapered bearing, but shows few details of its bearings and mounting. Some details are visible in Figure 1 on page 8 above.

b and c : As Figure 7, below, shows, the bearing at the bottom of the pillar allows the pillar to rotate on its axis and to move radially relative to the wheel. This allows the scriber frame to bring the screw tangential to the wheel and, as will be seen later, also allows a spring to press the screw against the edge of the wheel.

It is clear from the drawings that no axial movement of the pillar is possible, though it would seem that some is desirable to allow for differences in thermal expansion between the wooden frame and the brass pillar. However, Ramsden took great care to keep the temperature of his workshop even, and in any case the differences would be practically negligible over a 10 degree change (the coefficients of linear expansion of wood and brass are about 5 and 19 x 10^{-6} m/m K respectively). More important would be changes in length of the wooden parts with changing humidity. Happily, wood changes very little in length along the grain with changing humidity, but even so the wood would need to have been well seasoned and thoroughly sealed with varnish. The “intelligent workman” would know to insert adjusting shims between k and h to bring the screw frame to the correct height.

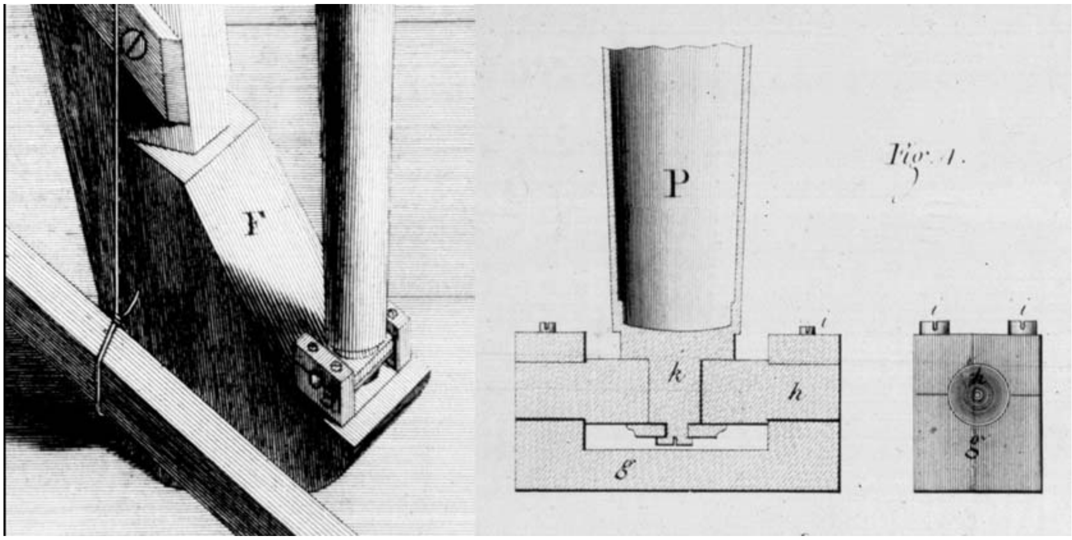

Figure 7

d : *the frame G in which the endless screw turns…*
Figure 8, page 15, below, shows the general arrangement of parts at the upper end of the pillar.

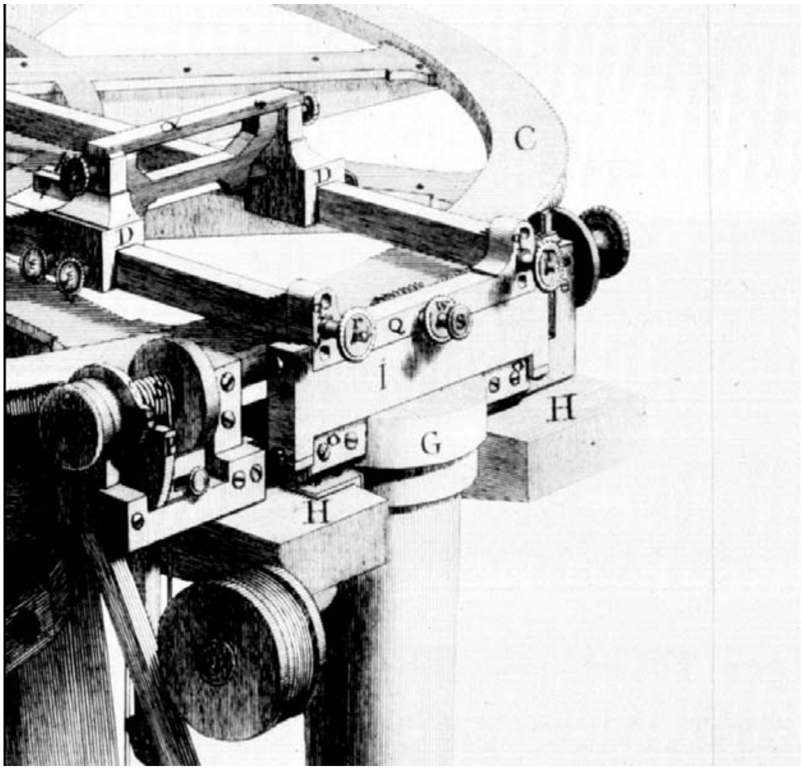

Figure 8

e and f *: two frustrums of cones …do not touch the cylindrical parts…*
At each end of the worm shaft the bearings are in the form of pairs of opposed cones (Figure 9 below). In a fast running bearing, it would be desirable to have only one pair of cones, with a parallel bearing at the other end, to allow for expansion of the shaft within its bearings as it heats up. However, the critical requirement is that there should be absolutely no end float (longitudinal movement) of the shaft, and differential expansion of the parts, the possibility of which Ramsden was well aware, is of secondary importance.

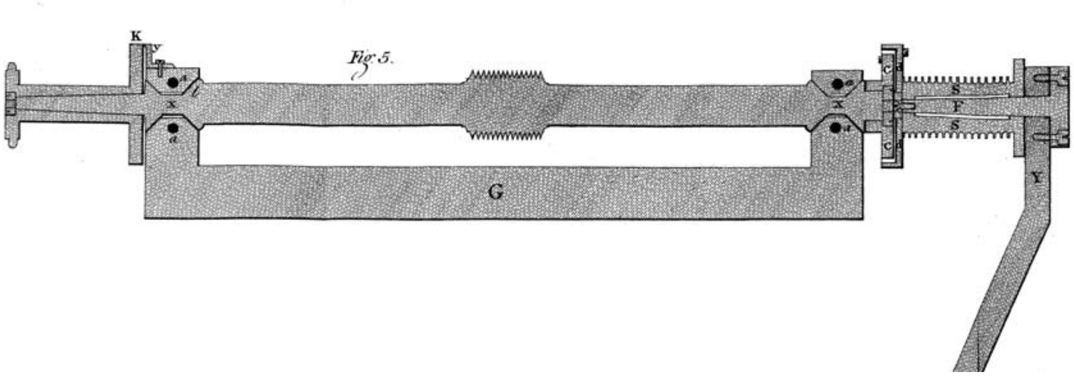

Figure 9

Opposed cones take care of axial and radial loads at the same time. It is important that the parallel part between the two cones should clear the bearing as it would not otherwise be possible to adjust the bearing caps to take up clearances at the conical parts (Figure 10 below).

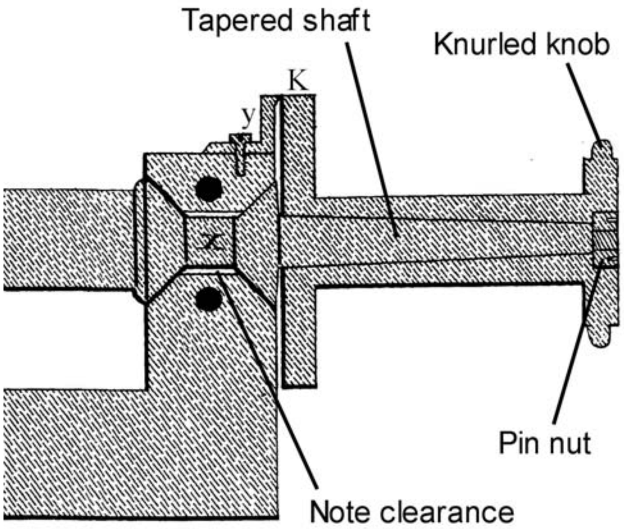

Figure 10

Ramsden's drawings show the "screw frame" as if viewed from the far side of the wheel, so that details of the bearing caps cannot be seen. These are shown in Figure 11, below. This machine[15] follows Ramsden's description very closely and was probably made by John Troughton in 1778[16]. The dowel pins allow the caps to be replaced in the same configuration as when they were machined and also prevent them being replaced on the wrong end.

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[15] Science Museum, London, inv.no. 1932 - 22

[16] S Johnston, personal communication.

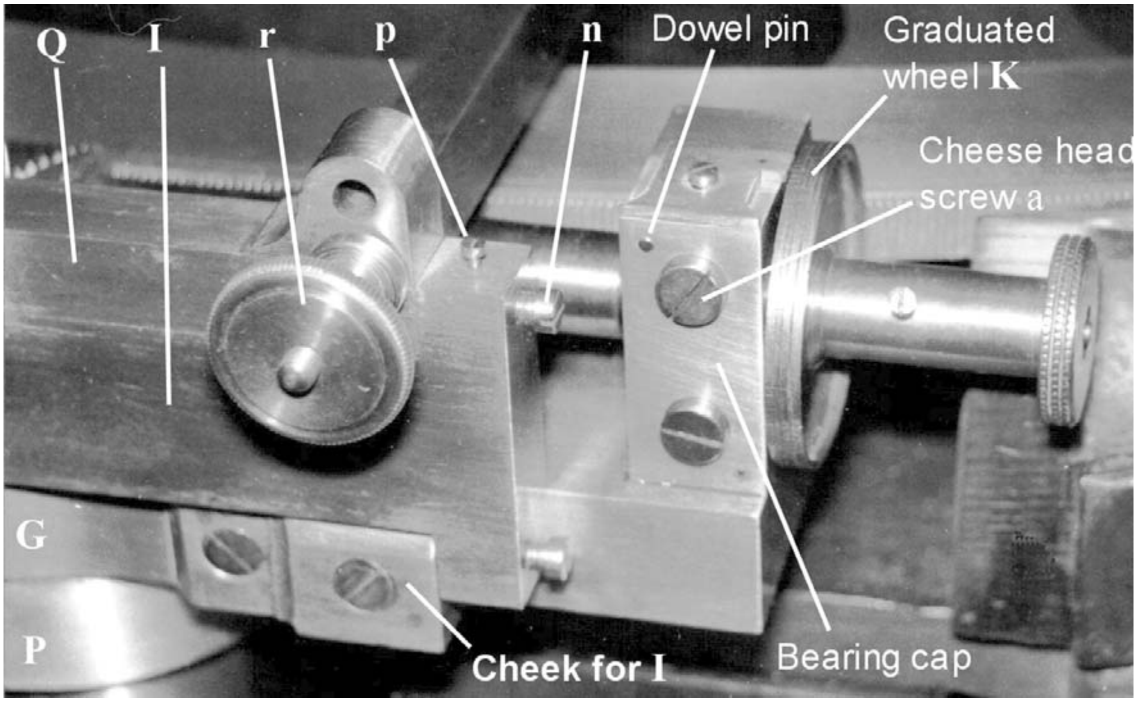

Figure 11

g : *wheel of brass K,*
The graduated wheel, K, shown in Figure 11, above, is shown in section in Figure 10, page 16, above. The drawing has been flipped to show the same orientation as in the photograph.

The wheel is fitted on to the tapered end of the worm shaft, to ensure accurate centering, and is held in place by a pin nut (Figure 11a) rather than by a screw, to preserve the centres between which the shaft was turned. Nuts of this period were either square and made by blacksmiths, or circular with pin holes and made by instrument and clock makers.

h : *H represents part of the stand…*
These cheeks are well-shown in Figure 8, page 15, above, and both cheeks can be seen in Figure 12 on page 18, below.

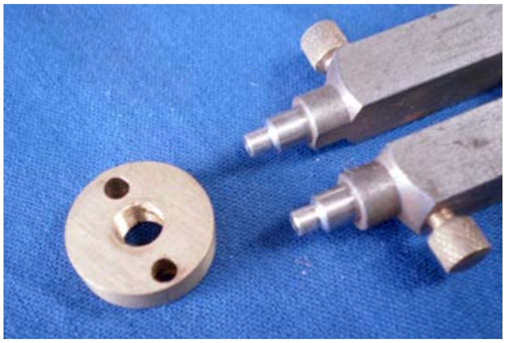

Figure 11a

TEXT page 6

a : See Figure 8, page 15.

b : *that side of the slit is faced with brass…*
A brass right angle is let into the top and right hand face of the left hand cheek H. This can just be seen in Figure 12 below, and is clearly shown in Figure 8.

c : *a steel spring…*
Figure 12 also shows on the right of the pillar the large folded leaf spring that hold the pillar P against the left hand cheek. Recall that the frame L is the frame that carries the scriber mechanism.

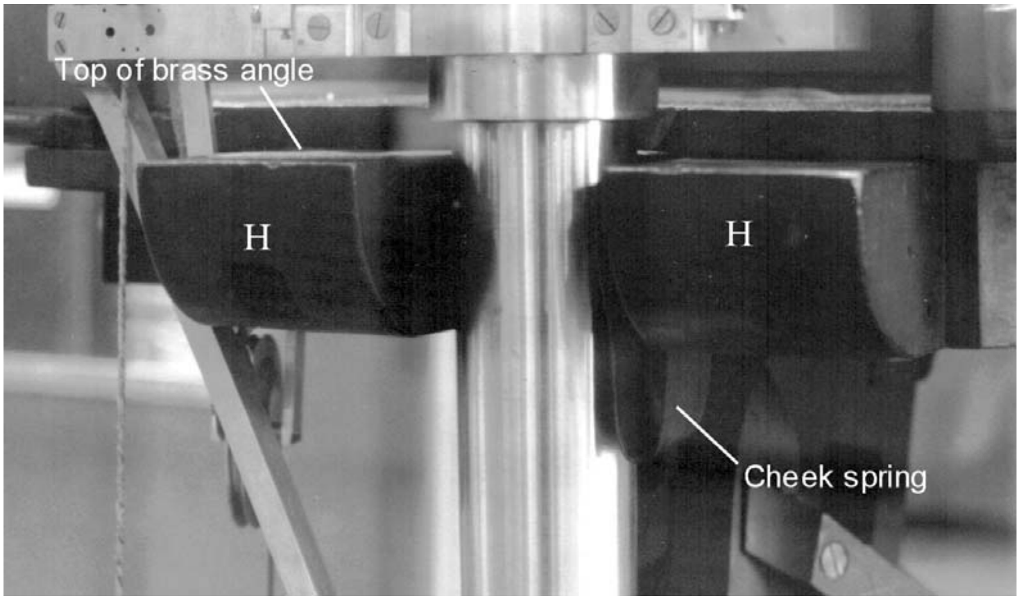

Figure 12

d and e : The general arrangement is shown in Figure 8 (page 15 above) and the details in Figure 13, below. The lower pair of conical-pointed screws of hardened and tempered steel, n, engage in conical holes in the sides of two cheeks screwed and dowelled into the face of the screw frame G (see Figure 11, page 17 above). The method of locking them with transverse steel screws p is not ideal as there is a risk of damaging the threads of screws n. Brass locking screws might have been better. The upper pair engage with Q, to which the scriber frame is attached.

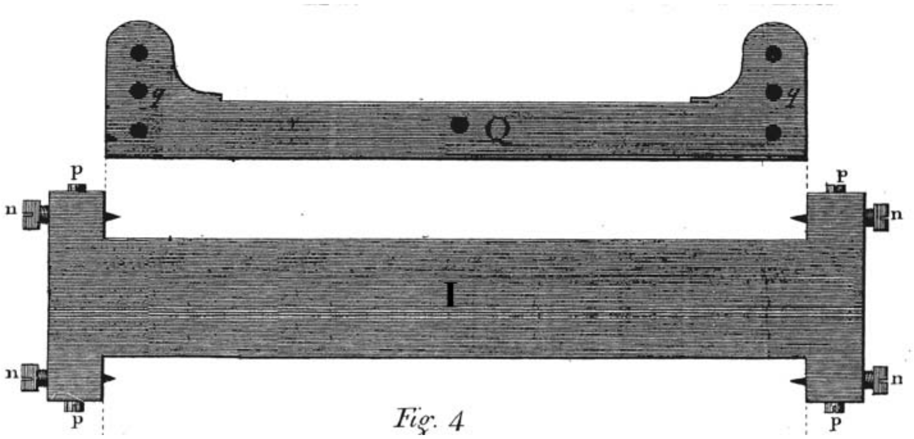

Figure 13

f, g and h :

Referring to Figure 14 and to Figure 15, which is an enhanced and enlarged version of Figure 4, it is now possible to bring together the functions of the various parts. Part Q is attached to the scriber frame L by finger nuts r. Screw s is threaded through Q and its tip bears on the spring T. This spring, acting through the top of the pillar, then causes the worm to engage with the edge of the wheel, and keeps the frame L in engagement with the dead centre on which the sextant is mounted, via the “angular” vee notch shown in Figure 3 (page 10). Parts Q and I form a shake-free articulation between the worm screw frame and the tracer support L. The diagram in Figure 16, page 22, below, which takes liberties with perspective, may help to make this clearer. Any eccentricty of the wheel bearing will not show up as varying depth of engagement of the worm.

It is important to realise that the central wheel bearing and the roller bearings that carry the wheel take no part in centring the worm and scriber frame. They simply allow the wheel to rotate on top of the frame, while the relative rotation between worm and wheel is about the dead centre that locates the instrument being divided, via two vee grooves (Figure 3, page 10 and Figure 17, page 23).

This arrangement was a developmental dead end. As the art of casting in iron advanced, later dividing engines united the central wheel bearing and the worm by means of rigid castings that held them in the correct relationship.

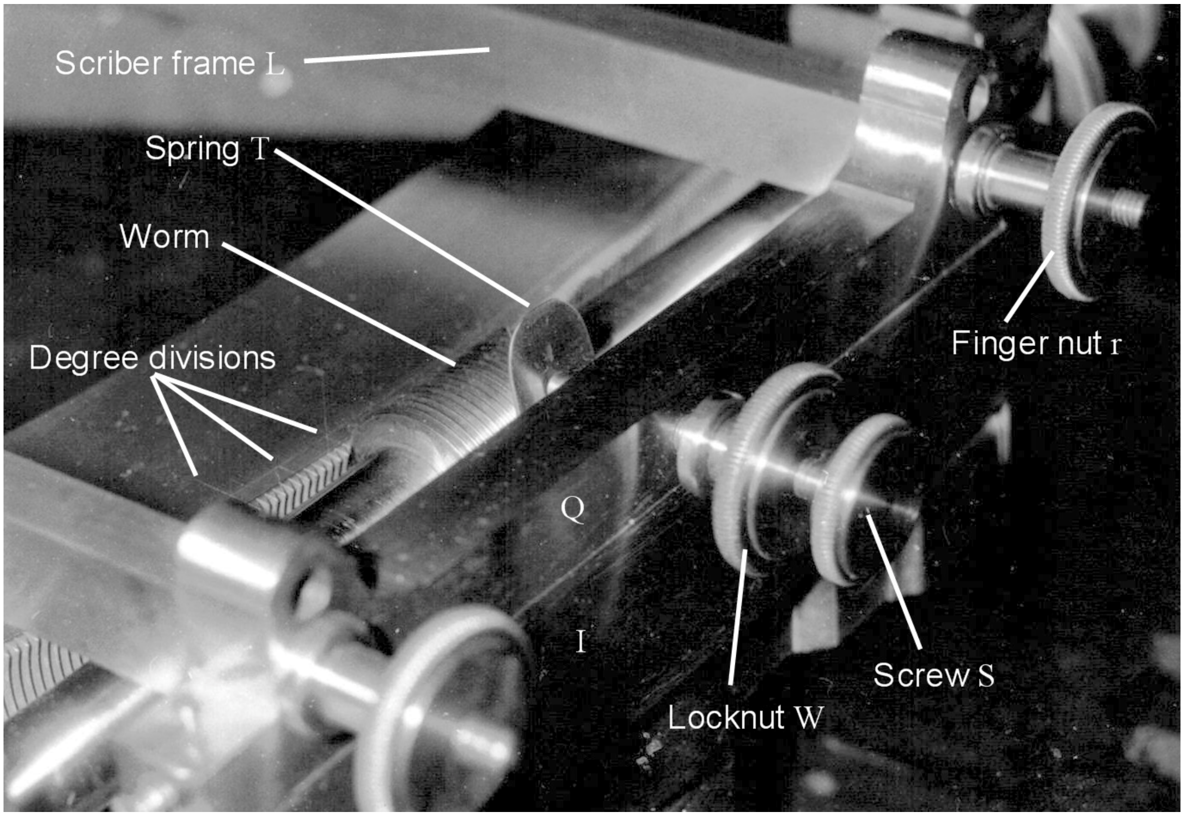
Scriber frame L
Spring T
Worm
Degree divisions
Finger nut r
Q
I
Screw S
Locknut W

Figure 14

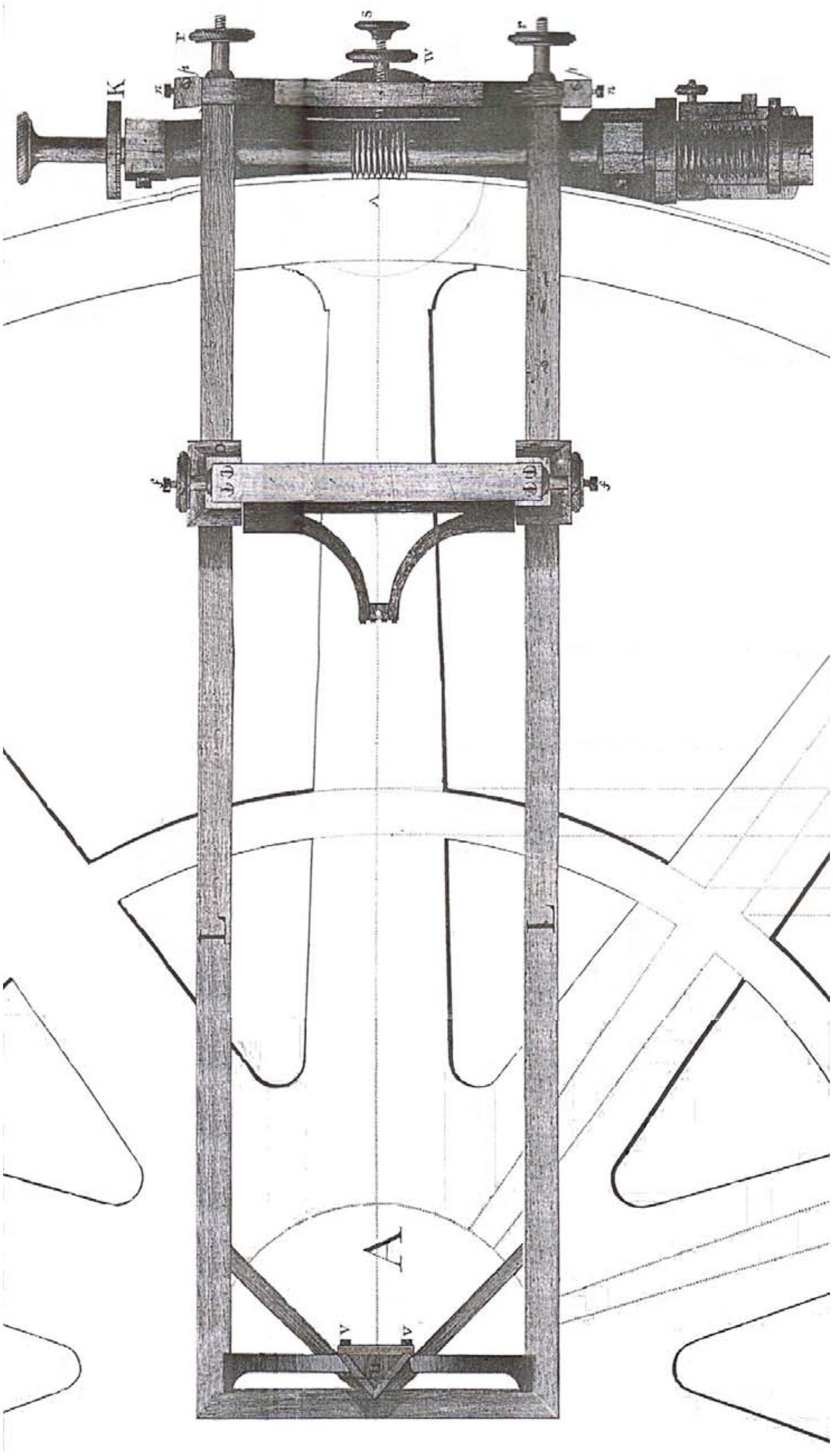

Figure 15

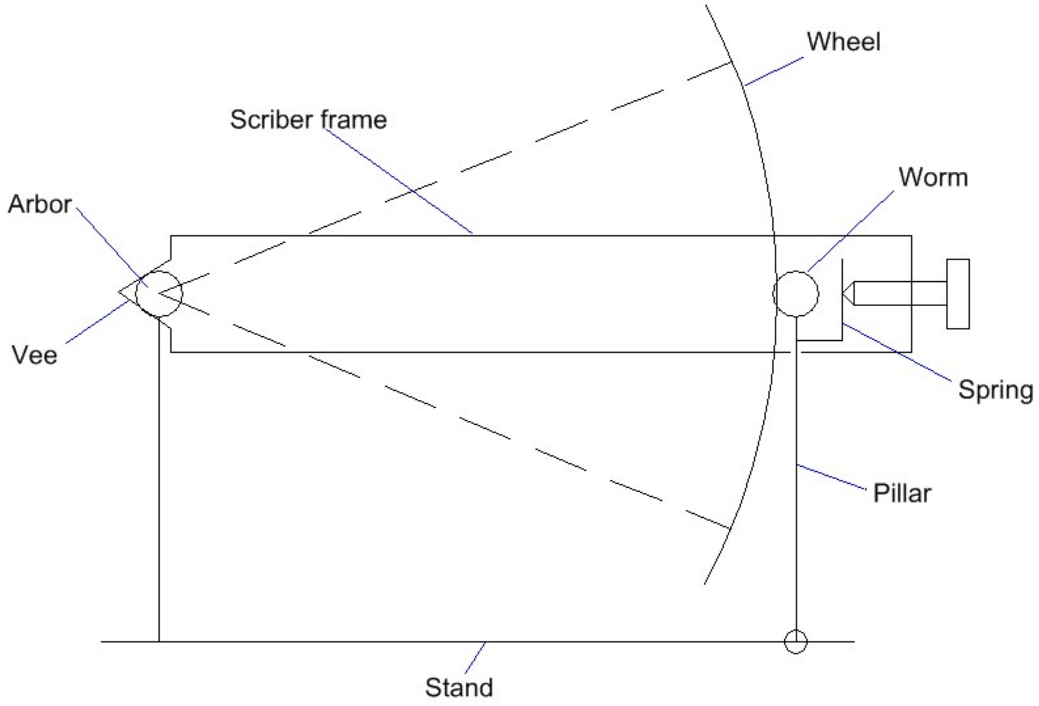

Figure 16

TEXT page 7

a and b : *prismatic slide.. the point of the arbor (d) resting in this notch..*

The third angle projections in Figure 17, (the plan above and the front view below), show the structure of the prismatic slide and Figure 18 on page 24 below illustrates the whole. A triangular pillar, u has a vee groove, k, at the bottom whose axis is parallel to the long axis of the frame L and lies on the radius of the wheel. The conical end of the arbor that carries the sextant sits in this groove and allows the frame and worm to move into place, while accurately locating the tracer along a radius. The slide is locked by means of the four screws, v, though a single screw through the centre of the plate would have served the same purpose (only two were used in Troughton's engine, shown in Figure 18).

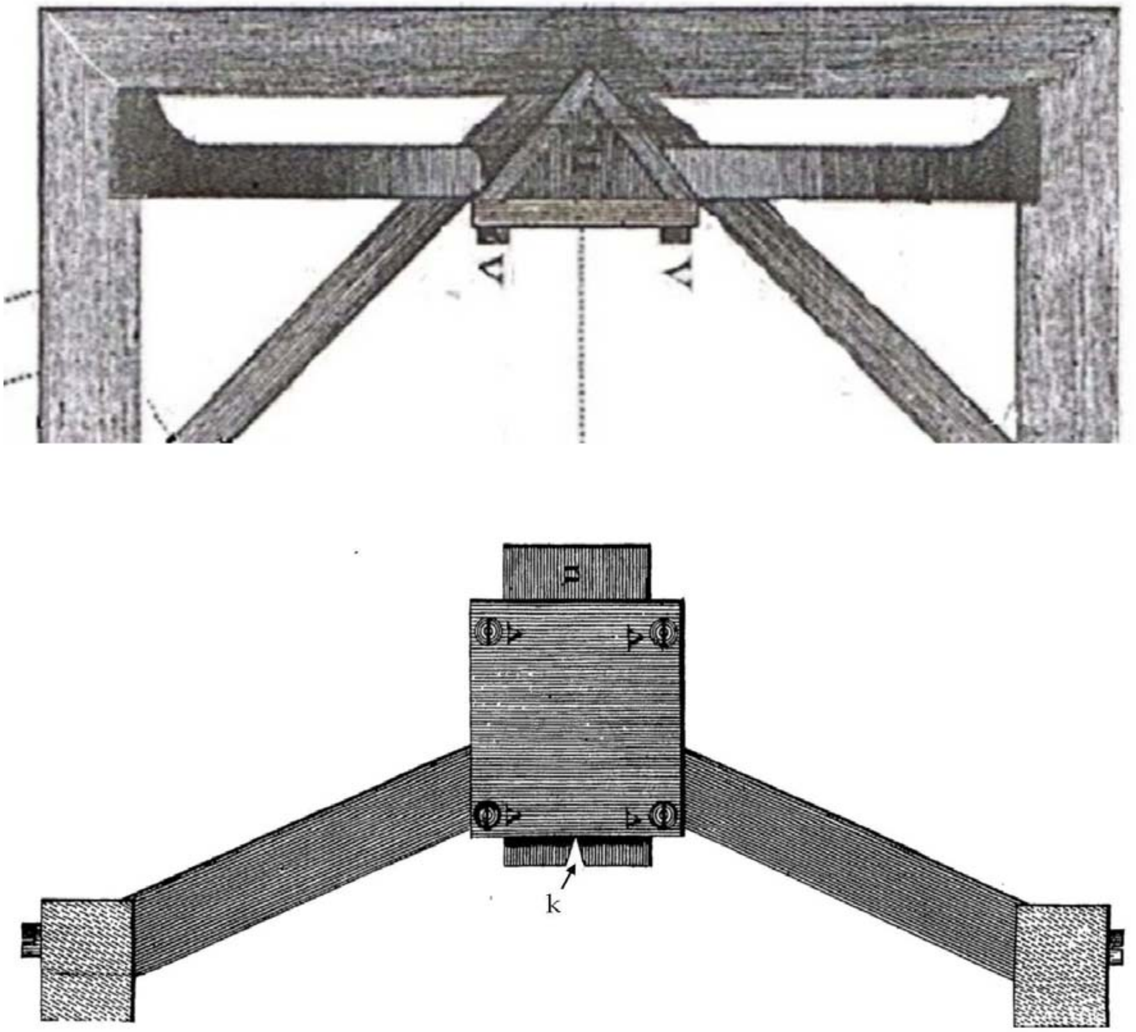

Figure 17

Ramsden’s reference to tilting presumably means tilting along the axis of the scriber frame, but the engine illustrated in a portrait of Ramsden from an engraving of 1790 shows that a steadying frame with two rollers bearing on the face of the wheel was later added to prevent lateral tilt (Frontispiece). Note that the tilting moment is greater, the closer the scriber is used to the centre. Figure 19 below shows how a scriber working at a radius of an 8 inch sextant would, if carelessly used, tend to tilt the frame more than it would at twice this radius, since more of the scriber frame lies outside its lines of support, shown in dotted blue. The tilting moment with the steadying frame would, however, then be transmitted to the periphery of the wheel, perhaps the lesser of two evils.

In his first dividing engine, the scribing frame reaches across the full diameter of the worm wheel and has a steadying bar at right angles to it, though it is possible that this was added later by the purchaser, Bochard de Saron.

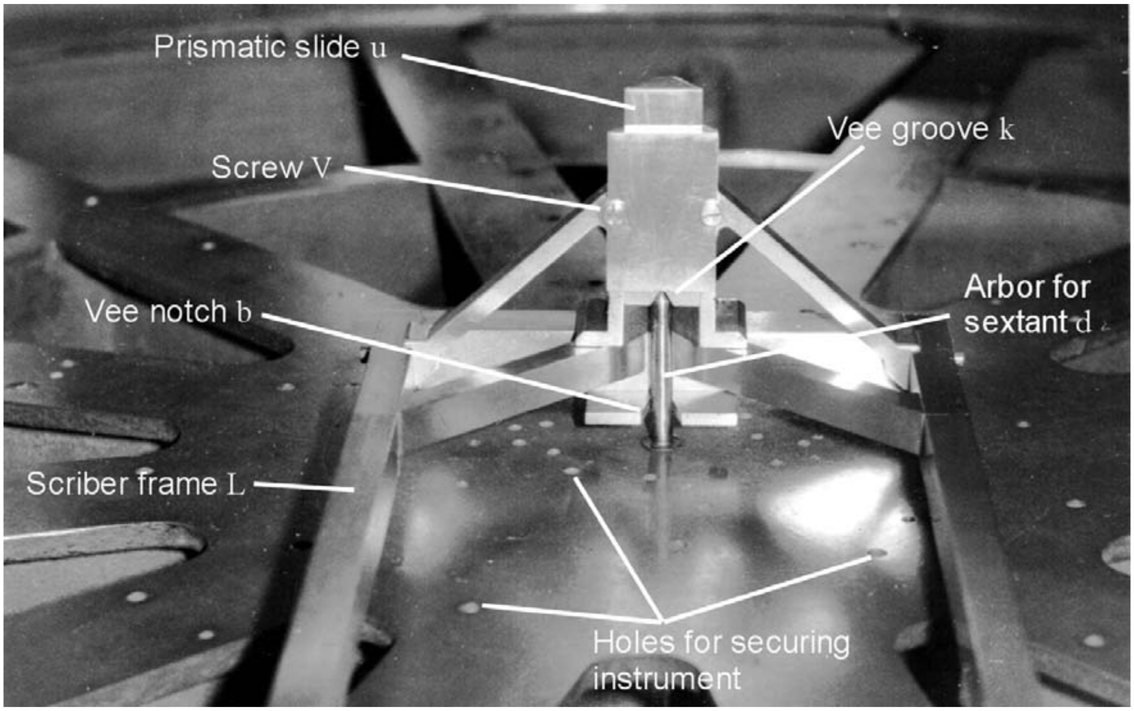

Figure 18

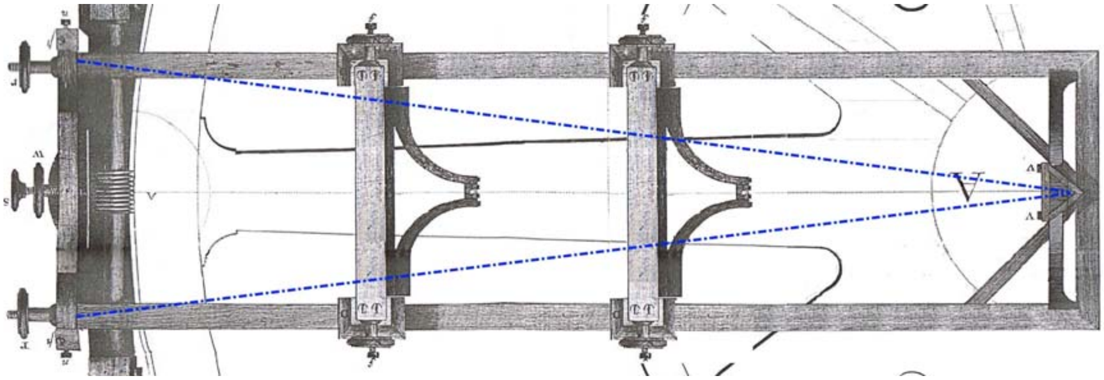

Figure 19

c : *one of these screws, which was intended for ratching or cutting the teeth was notched across the threads,…*

This is the process which we now call hobbing. When a rotating screw is pressed against the rim of a wheel, the angle of the thread to its long axis tends to cause the wheel to rotate, a process progressively made more certain as teeth are excavated by the cutting edges of the notches. Figure 20 below shows on the left a hob made in the same way that Ramsden describes and on the right, a modern hob of a size that would cut teeth of about the same pitch as on Ramsden's engine. This latter hob is relieved behind the cutting faces in such a way that the tooth form is preserved after sharpening the faces. Nowadays, the hob and the wheel being cut are geared together, so that they turn at the correct speed to generate the number of teeth required without risk of slippage. When they are not so geared, the process is called free-wheel hobbing.

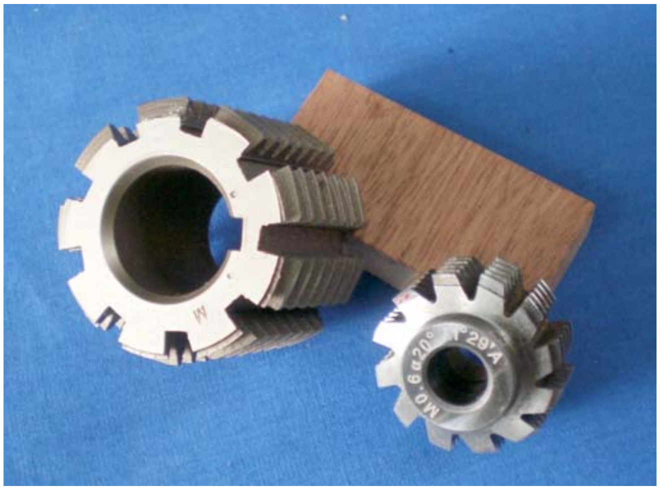

Figure 20

Ramsden perhaps glosses over the difficulties inherent in free wheel hobbing. The rear flank of the cutter drives the wheel while the front flank does the cutting. The drive and hence the cut tends to be intermittent when using a hob with "notches" parallel to the axis of the hob, and unless the next cutting edge engages the workpiece before the preceding one leaves it, there can be considerable vibration and slippage. Edward Troughton wrote in 1830 about the difficulties he and his brother experienced with the technique [17]. However, Ramsden did not write that the notches he cut were parallel to the hob's axis and he may well have made the teeth spiral, the solution Edward Troughton eventually adopted. Figure 21 shows a spiral-fluted tap used by the author to free-wheel hob a large worm wheel of 360 teeth for a dividing device.

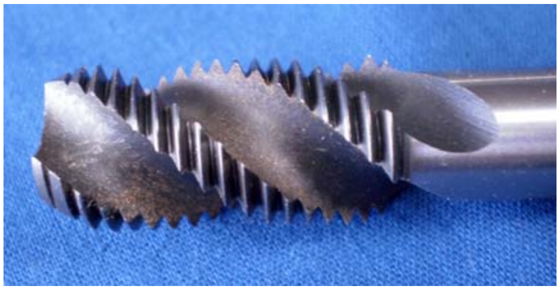

Figure 21

d : *set off the chord of 60 degrees…*

A chord of a circle is a straight line that joins two points on it. Secondary-school children used to know that a chord equal in length to the radius of the circle

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[17] Edinburgh Encyclopaedia X. (Edinburgh, 1830) p. 355.

marks off exactly 60 degrees (the two radii and the chord form an equilateral triangle and the sum of the internal angles is 180 degrees). We are used to being able to produce screw threads of known pitches, and from that we can calculate the required radius of the circle. Ramsden was not in that position. He had to produce the thread and make the circle fit by this preliminary trial using a 60 degree segment.

TEXT page 8

a : *a pair of beam compasses…*
Instead of the familiar hinged pair of dividers, when setting out relatively large radii the two points are connected by a long beam and one point is able to be finely adjusted in position (Figure 22, below).

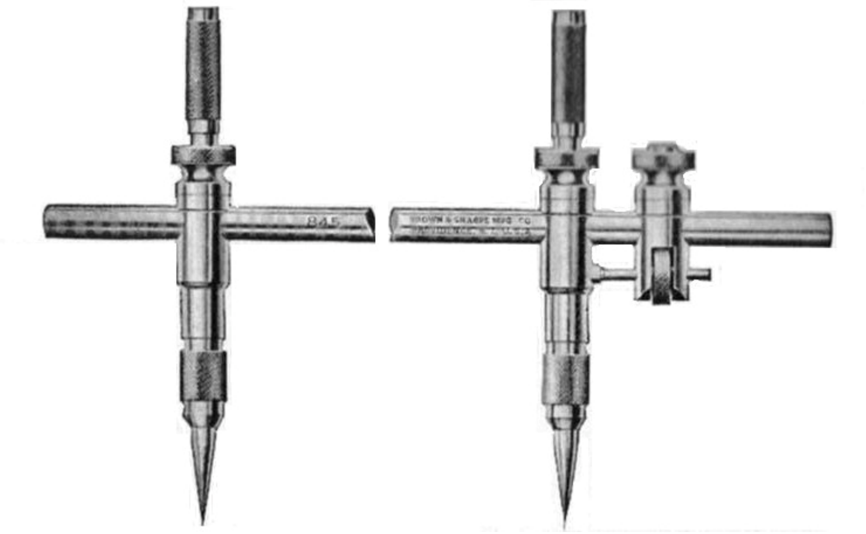

Figure 22

Like Graham, Bird, John Troughton, also highly skilled instrument makers, Ramsden was a master of the beam compasses. Before machine dividing became possible, every instrument had to be divided by hand and, through daily practice, experts had a highly developed sense of touch that enabled them to feel the points slipping into a finely scribed line or dot.

b : *then half the depth of the threads…*
This adds half the tooth depth to the pitch circle, the imaginary circle along which the tooth pitch is measured and from which the tooth proportions are given.

c : *a hollow was then turned on the edge of the wheel…*
The scalloping of the edge of the wheel, visible at the far left of Figure 14 (page 20, above), increases the area of contact between the worm and the wheel.

d : *which after this ought not to be removed…*
The centre hole for the arbor about which the wheel will turn relative to the worm will be carried in piece D. Removing it could possible de-centre it and lead to centring errors, despite all the precautions taken to ensure concentricity, such as turning between centres on an arbor and making taper fits. For the same reason, the index arm bearing of a sextant should be removed from the frame only for the most pressing reasons.

e and f : *the circle was divided…by continual bisections*
Chords of equal length are stepped off with a pair of dividers around the circle by trial and error until, after the required number of steps, one arrives back precisely at the starting point. After the initial quinquisection, each fifth part would be divided into three by a similar process. This was followed by successive bisections. The process up to the first bisection is shown in Figure 23, below.

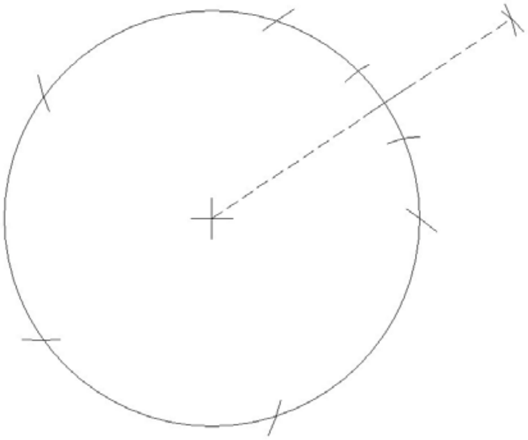

Figure 23

Alternatively, the circle could be divided into six by stepping around a chord equal to the radius and then be further divided by successive bisections. In a sense, this is a “purer” method, as it involves no trial and error and extraneous dots, but, as Ramsden shows, in his hands it had no practical advantage.

TEXT page 9

a : *every 135 revolutions…*
i.e. every 135\9 = every 15 degrees.

b : *as the coincidence of the fixed wire with an intersection could be more exactly determined than with a dot or a division…*
The human eye-brain combination seems to be better at placing a line midway between two lines or at an intersection, than at placing a line in the centre of an object.

c : *thin piece of brass...a silver wire…in line to the centre of the wheel…*
This is shown in Figure 24, below, which is an enhanced reproduction of the original Figure 7 in Plate II. The brass is ghosted in on top of the scale for clarity, as Ramsden's footnote explains. Silver can be drawn out into very fine wire.

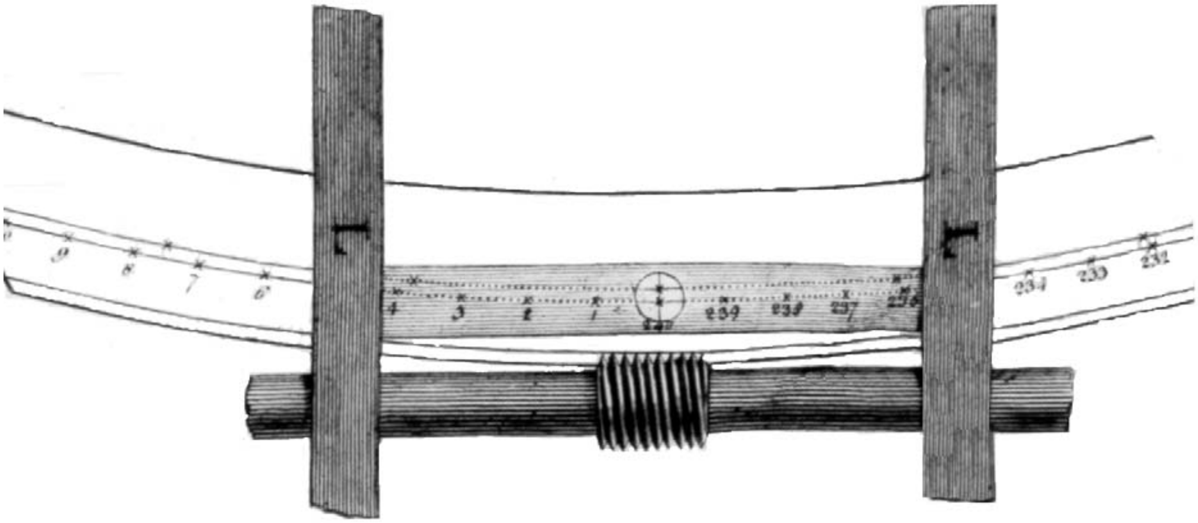

Figure 24

d : *the division marked 10 on the circle K…*
Recall that the edge of K, which is attached to the right hand end of the worm shaft, is divided into 60, numbered at every 6th division from 1 to 10. Modern practice would be to number from 0 to 9, with 0 corresponding to Ramsden's 10.

e : *the intersection marked 240…*
Again, modern practice would have numbered it as 0. The wire is shown over this intersection in Figure 24, above.

f : *came nearly to the wire;…*
It would come exactly to the wire only if the teeth had been excavated to their full depth.

TEXT page 10

a : *and I proceeded in this manner till the teeth were marked round the full circumference of the wheel.*
Thus, in 240 steps of 1½ degrees, nine turns each step, he has the beginnings of all the teeth. Any error in the hob or the identical worm will be distributed amongst all the steps, whereas if he had simply wound the hob around continuously, it would have been concentrated in one tooth at the end

b : *ratching the wheel about 300 times round…*
At six turns per degree, this comes to an astonishing 648,000 turns. Truly “Genius is an infinite capacity for taking pains”. Perhaps he set an apprentice to the task.

c : *and the teeth were reduced to a perfect equality.*
In free wheel hobbing, in which the cutter also impels the wheel to turn, this is not so in theory, as slightly more metal is removed from one flank of the tooth than the other. The very last tooth to receive the cut will be slightly thinner than the one ahead. In practice, especially with many fine teeth, the differences are immeasurably small. If one can be assured of equality of all the teeth, then there always being exactly 360 degrees in a full circle, six turns must cover one degree exactly.

TEXT page 11

a : *a ratchet wheel, having 60 teeth,…*
(See Figure 25, page 30) This allows portions of a whole turn. Since each turn rotates the wheel 10 minutes, one tooth is the equivalent of 10 seconds. The finest divisions ever used on a sextant were each of 10 minutes, which subtended 5 minutes of a circle or half a turn. When it came to dividing the vernier, the possibility of dividing to parts of a minute was needed. An extended vernier reading to 10 seconds subtends 9 minute 55 seconds, so it is possible that the final setting of the worm was by hand, using the divided wheel K on the right hand end of the worm to obtain a setting to 5 seconds.

The teeth themselves of course had to be accurately divided and cut. There are about sixteen threads on the cylinder S. Some are needed for the catgut line that turns it. In practice, the largest division cut was likely to have been one degree, or nine turns. It also illustrates that a method had already been devised for routinely cutting screw threads on large workpieces.

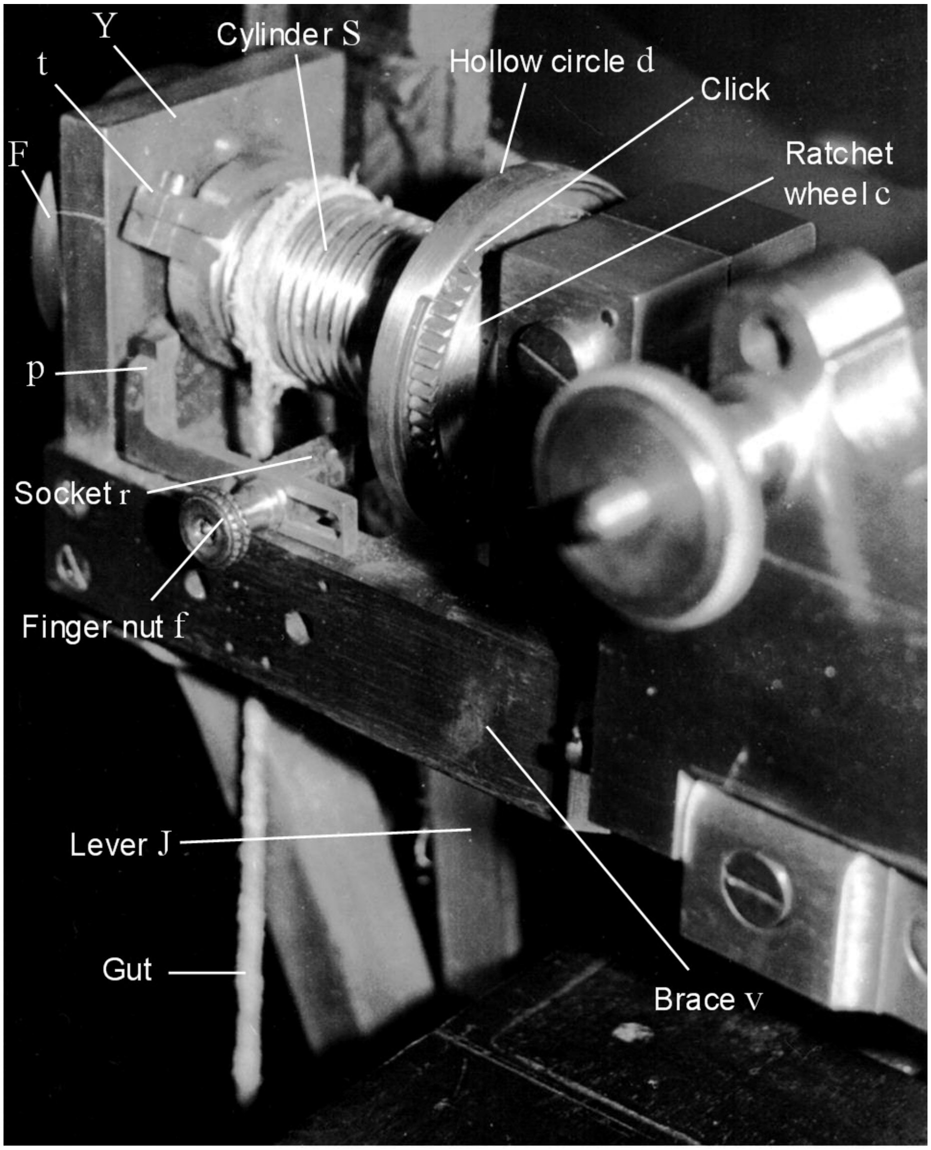

Figure 25

b : *two clicks*…
A click or pawl is a piece of brass or steel shaped and spring loaded so that the teeth of a ratchet wheel can slide under it in one direction of rotation, but engage positively with it in the other. In a clock or watch, it is used, e.g. to prevent a spring barrel unwinding, but in this dividing engine the system of ratchet wheel and click is used in reverse, to impart motion in only one direction. Ramsden used two clicks at each end of a diameter, so that there would be no possibility of a bending force being introduced.

c : *a strong steel arbor…*
Note from the section drawing of Figure 26 that is tapered to ensure accurate centring.

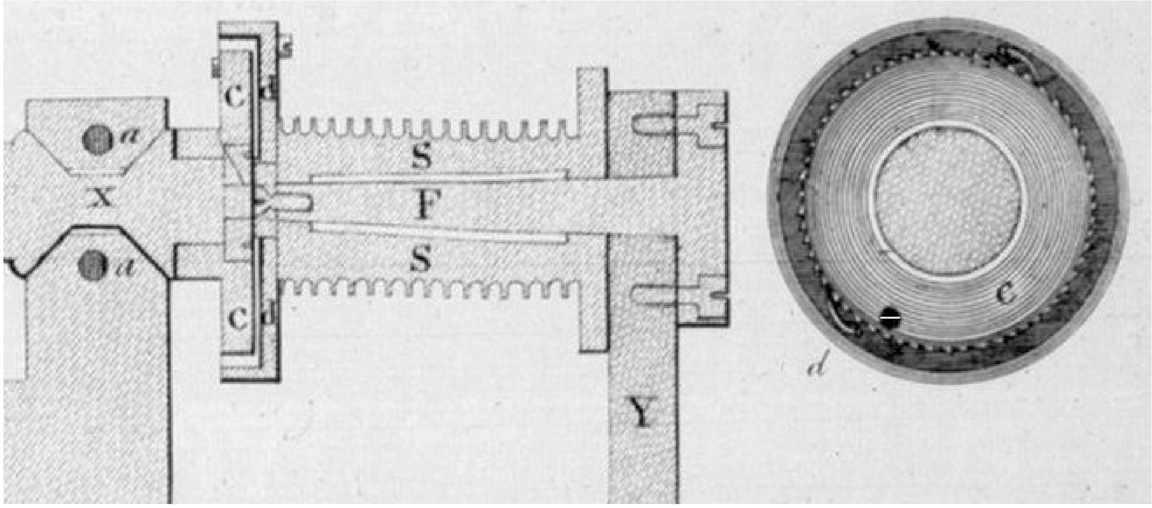

Figure 26

d : *a spiral groove or thread…*
Accuracy is less important here, as only the starting and stopping points of the rotation need to be precisely set.

e : *a steel tooth…*
This is a little hard to see on the section drawing, to the right in Plate III and labelled n, and it is completely out of view in Ramsden's original elevation, which shows the *back* of the screw frame. For clarity, I have ghosted it in red in Figure 27 (next page). Note that it and the end of lever J are placed below the centre line of S, so that the stop screw x can strike the top of J squarely, bringing S to a positive stop, without any tendency to displace the lever. For the same reason, at this point, J will be square to the axis of S.

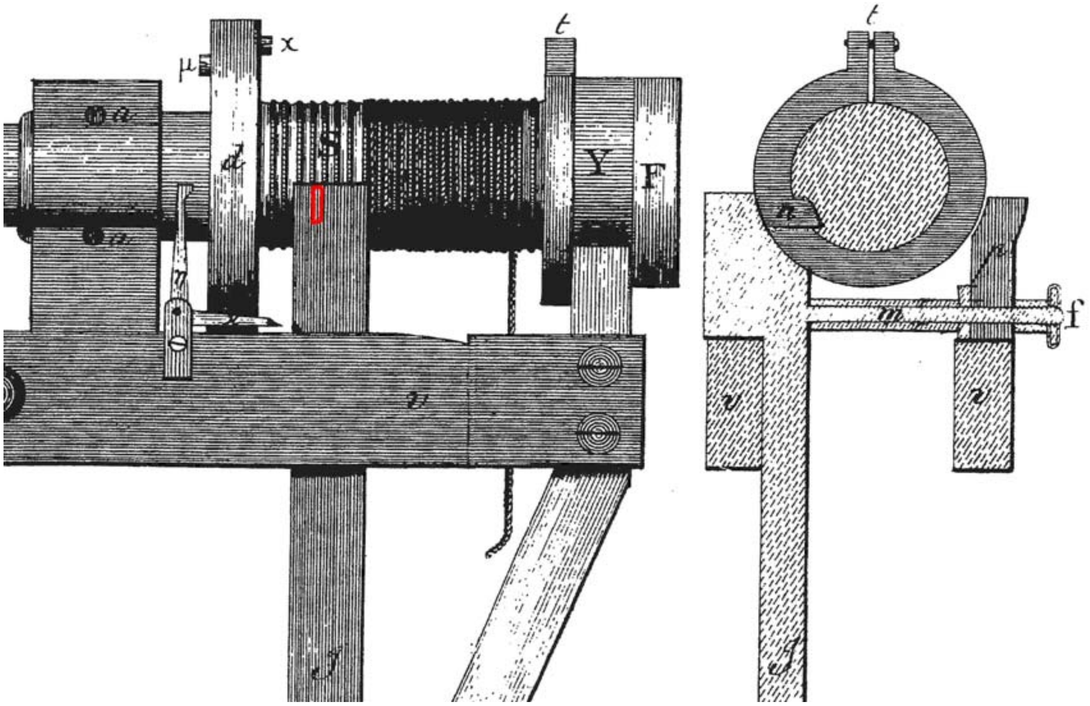

Figure 27

f : *on which a brass socket turns…*
This seems to be what we might now call a spacer, and as drawn in Figure 27 it can turn only when finger nut f is loose. It seems to be the steel pin m that passes through the slot in p, not the “socket”.

g : *serves to regulate the number of revolutions…*
The next paragraph puts everything together (see also Plate 1 of the text). The treadle was probably actuated until the top of lever J brought the cylinder S to a halt, by striking the screw head x. Holding this position, the graduated wheel K on the other end of the screw was then turned to a starting position, as the ratchet wheel allowed. The treadle was then probably slowly released and turns counted. At the requisite number of turns, the stop p and the ring t (which has a clamp screw to enable it to be rotated and locked into position) were then positioned so that the starting point for rotation was established. The start and stop positions would then be carefully checked by reference to the graduated wheel K before graduating began.

h : a *strong gut*…
Sometimes called catgut, this was usually made from the intestinal wall of the sheep or goat and was the strongest and most reliable string available to clock and instrument makers.

TEXT page 12

a : *the angular lever η…*
This is the L-shaped lever to the left of d in Figure 27 (page 32).

b : *a small chamfor…*
This can just be seen as a black triangle on the left hand edge of the lever J (Figure 27, page 32). When the angled tip of the horizontal limb of the L, labelled κ, enters it, the vertical limb is tilted so that its top stops the rotation of the worm shaft by engaging with the screw μ that is set into the face of the ratchet wheel (see Figure 26, right). An eighteenth century clockmaker would recognise this as an adaptation of the fusee iron, a device for preventing disastrous over-winding of a clock fitted with a fusee.

c : *by a small spring…*
Though not shown, this would have been a small leaf spring rivetted to the horizontal part of the lever.

d : Now follows the description of the scriber mechanism shown in Figure 29 and in the photograph of Figure 30, next page. The double-hinged linkage allows the scriber to be lifted of the workpiece and re-positioned for the next stroke. Examination of sextants of the period shows no hint of a tendency for the lines to be over-long or for them to vary in depth and width, so either extraordinary skill and concentration was involved or some strategies to reduce error were introduced. The author can vouch for the frustration that results from making one line out of many too long and thus spoiling the workpiece.

Regularity of length could at least be assured by scribing circumferential lines while the sextant was mounted on the lathe (see Figure 31, belwo, page 35), so that the scriber could slip into the line at the start of the stroke and be felt to slip into another at the end. An obvious solution is to fit a stop to govern the depth and hence width of stroke. Less easy is to have a system to regulate the length. In the scale shown, it changes every third and fifteenth stroke. Perhaps there was no incentive to de-skill the process.

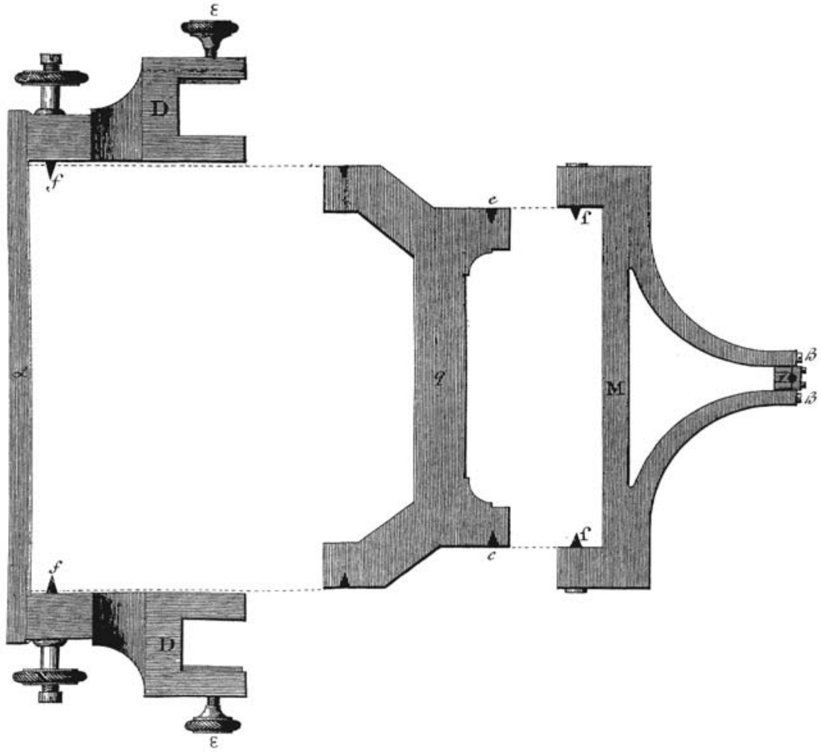

Figure 29

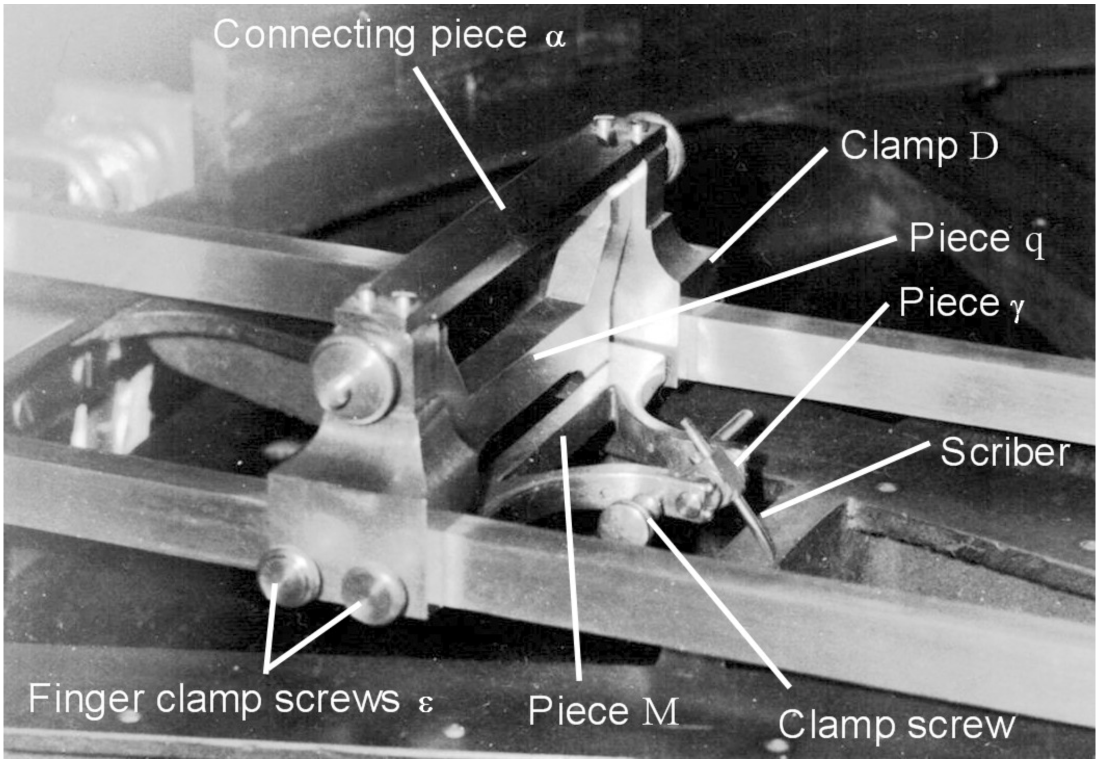

Figure 30

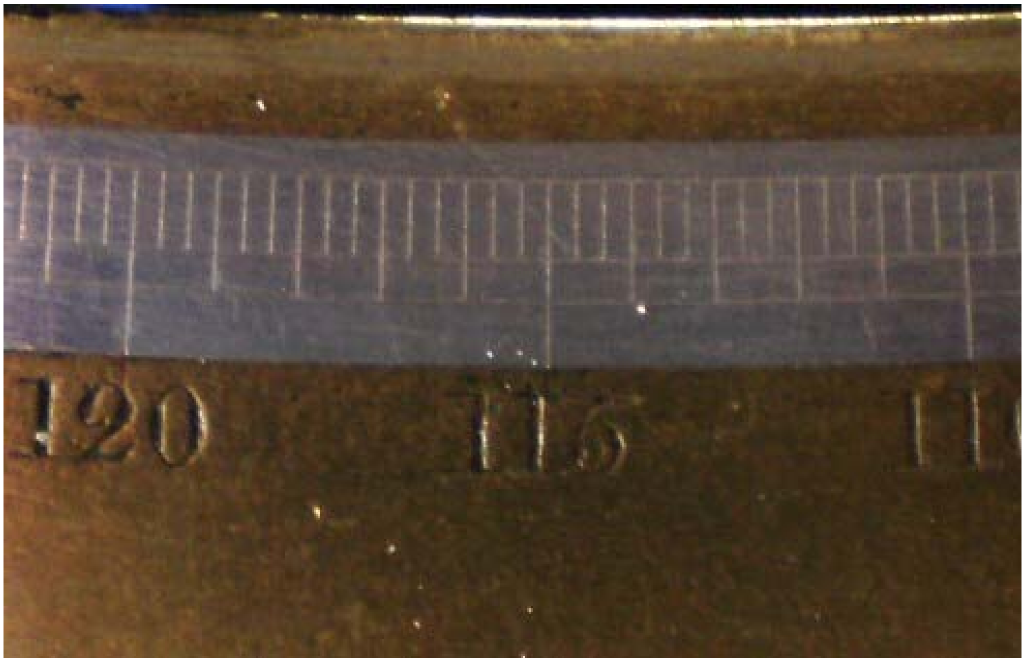

Figure 31

e : *cut divisions on an inclined plane..*
There is an obvious need for this when cutting the vernier scale, which is bevelled so as to have a feather edge. Ramsden also produced sextants having a bevelled limb, so that the scales of the vernier and arc were in the same plane, reducing a slightly annoying difference in viewing contrast of the two scales.

f : It seems that John Troughton found this was inadequate, as he has provided an additional clamping screw, shown in Figure 30.

PART 2

A COMMENTARY ON
JESSE RAMSDEN'S
DESCRIPTION OF THE ENGINE
BY WHICH THE
ENDLESS SCREW
OF THE
DIVIDING ENGINE WAS CUT

INTRODUCTION

Principle

If a tool is traversed at a constant rate parallel to the axis of a rotating cylindrical workpiece and fed into the workpiece, a regular helix will be generated on the surface of the workpiece. If the tool is progressively fed deeper into the workpiece, a helical thread of constant pitch will be formed. If the tool is traversed at different rates, threads of different pitches will be generated. This is the basis of the screw-cutting lathe.

Practice

Nearly always, the carriage that carries the tool is caused to traverse by means of a long screw, the lead screw, that rotates in bearings attached to the bed of the machine. The screw passes through a nut attached to the carriage so that the latter is caused to move longitudinally as the screw rotates. The pitch of the thread is changed by varying the ratio between the rate of rotation of the workpiece and the rate of rotation of the lead screw. Usually, this is done by varying the ratio of a chain of gears that connects the two.

Some history

Henry Maudslay (1771 to 1831) in many histories of machine tools is credited with inventing the screw cutting lathe. While it is true that he probably introduced it in a general-purpose form that easily allowed threads of different pitches to be produced on workpieces of various lengths, we shall see from Ramsden's account, that the principles were known well before Maudslay's birth.

It is easy to forget that textbooks of engineering workshop technology did not exist. It was the purpose of apprenticeships that lasted five or even seven years to transmit knowledge of techniques. The historian, looking for surviving realia and documentary evidence, is perhaps inclined to fall into the trap of thinking that what remains is all that there ever was. On the contrary, machines that had worn out or been superseded were unsentimentally scrapped and re-cycled; and craft skills were passed on by word of mouth and precept.

Leaving aside the adaptability of Maudslay's lathe, there are remarkable similarities between his and Ramsden's. Both had prismatic beds, were of similar size, and were powered by hand. Both had the headstock at the right hand end instead of the left end, usual in modern lathes, and both used change gears to vary the pitch of the thread to be cut.

Producing the original screw

Accounts of the screw-cutting lathe tend to gloss over how the original leadscrew was produced, at least one author averring that a paper template was glued to the blank workpiece and the thread produced by accurately filing it by hand[18].

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[18] Chapman, A., *Dividing the Circle*, p 131. Chichester, 1990.

This may well have been true of short and coarse threads produced in wood for olive presses and the like. However, the pitch of Ramsden's leadscrew was about 2mm and certainly would not have been produced in this way.

It is known that Maudslay produced his by feeding a knife tool at an angle to the axis of the rotating cylindrical workpiece and scalloped to fit its outside. The tool would then be carried along at a rate dependent on the angle and generate a helix. This was done first in a soft metal, which was then used as a leadscrew to produce another leadscrew in a harder metal. This was in about 1800 and it is likely that the technique was a well-known craft skill[19]. Figure 32 attempts to illustrate this diagramatically.

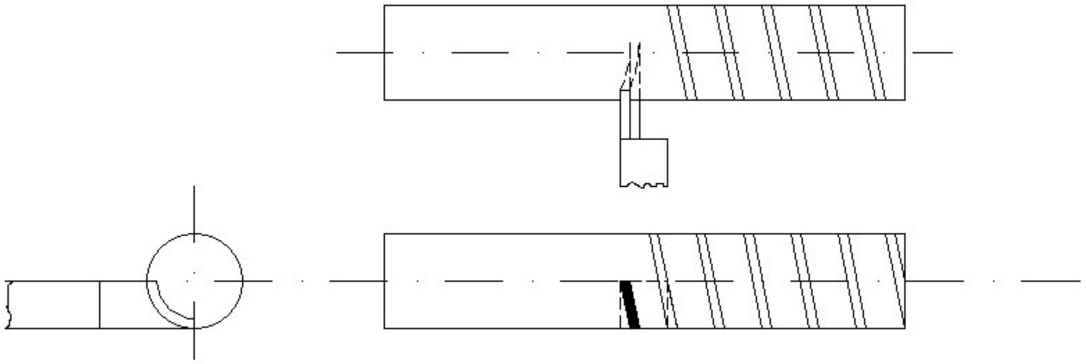

Figure 32

When no accuracy was required, screws could be produced by hand chasing. What is in effect a short segment of thread on the end of a tool (Fig 33) would be fed into the rotating workpiece by hand and the tool would be carried along by the thread form, cutting the thread as it went. The technique required great skill and was probably used to originate mainly fine threads in brass, though it was used as a finishing process for larger threads well into the twentieth century.

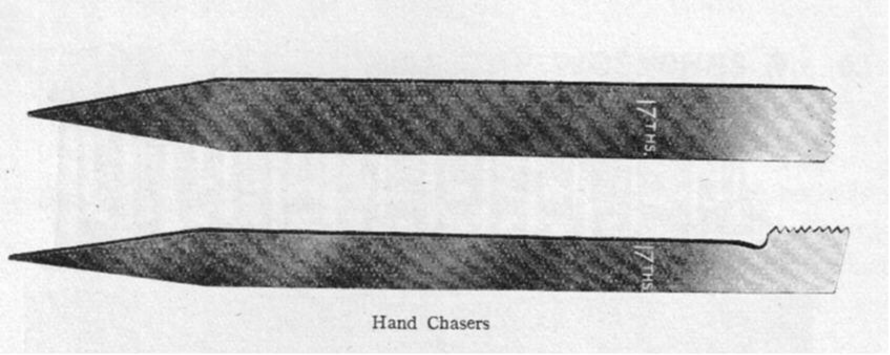

Fig 33

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[19] John Smeaton described how he had visited Henry Hindley of York in 1741 and been shown his screw-cutting lathe. (Phil Trans Roy Soc Lond, 1786, LXXVI.: 27)

A means of feeding the tool into the work in a controlled way is needed in a practical metal-working lathe. This usually takes the form of a dovetailed slide controlled by a short leadscrew that feeds in the slide and the tool attached to its top at right angles to the lathe's axis. As well as feeding in the tools when screw cutting, it can also generate a flat surface on the face of a rotating workpiece. Now known as the cross slide, in the eighteenth century it was more commonly known as the slide rest. Adding a further slide, the top slide, above this, that can be rotated at various angles to the lathe's axis, allows the generation of conical surfaces.

Though he is often credited with its invention, Maudslay never claimed to have invented the slide rest. Joseph Bramah (1748 – 1814), a near contemporary of Ramsden, certainly knew of it, Jacques de Vaucanson 1709 – 1782) had included one in his lathe of about 1750 (perhaps later) and it was almost certainly known about long before it was documented.

Figure 34, page 61, below, is a modified photograph which the Smithsonian Institution kindly provided to me about 25 years ago. It first appeared in Part I of the Smithsonian Report for 1890[20], and the lathe, like the dividing engine, was donated to the Institution, probably in that year, by Dr Henry Morton. I have added labels to it. Plate IV, from Ramsden's original account, has been digitally enhanced and repays study at increased magnification. Figure 8 in the plate is the view from above and Figure 9 is the view from the front. It will be seen that the Morton lathe has not been constructed exactly as in the plate, but the differences are minor and not unusual when a "one off" tool is constructed and only later illustrated.

Regularity of pitch and its degradation

In Ramsden's dividing engines, regularity of screw pitch was rather more important that the pitch being of a particular length. The long nut would tend to average out irregularities (see note 5, below), but several other factors militate against this regularity. For example, if the thrust faces of the leadscrew bearing are not accurately at right angles to the axis of rotation, the leadscrew will move back and forth slightly with each revolution of the screw and a periodic error will appear on the workpiece. Ramsden used a conical thrust bearing which avoided this source of error.

Slackness in the bearings that guide the rotation of the workpiece can lead to random errors, while eccentricity of the gear wheels can cause periodic errors. A more subtle source of errors arises from the tooth form of the gears that link the two shafts. If the form of the gear teeth is such that the velocity ratio varies as a given tooth moves in and out of engagement, this will be reproduced periodically on the workpiece. In Ramsden's day, clock gears invariably used teeth of

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[20] Annual Report of the Board of the Regents of the Smithsonian Institute. 1890. Facing page 136 (the report as it relates to Ramsden relies almost exclusively on Ramsden's own words).

cycloidal form (or an approximation to it) and it is not possible to produce practical gears of this form that also have an unvarying velocity ratio[21].

Ramsden was well educated and he had had an unusually extensive mathematical education for someone of his position, so it is quite possible that he was aware of the more satisfactory involute gear form and produced gears of this type. Certainly, the teeth of his circular engine, generated as they were by a hob having teeth with straight flanks, were of involute form.

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[21] Davis, W.O.,*Gears for Small Mechanisms*,p20. Hinckley, 1953

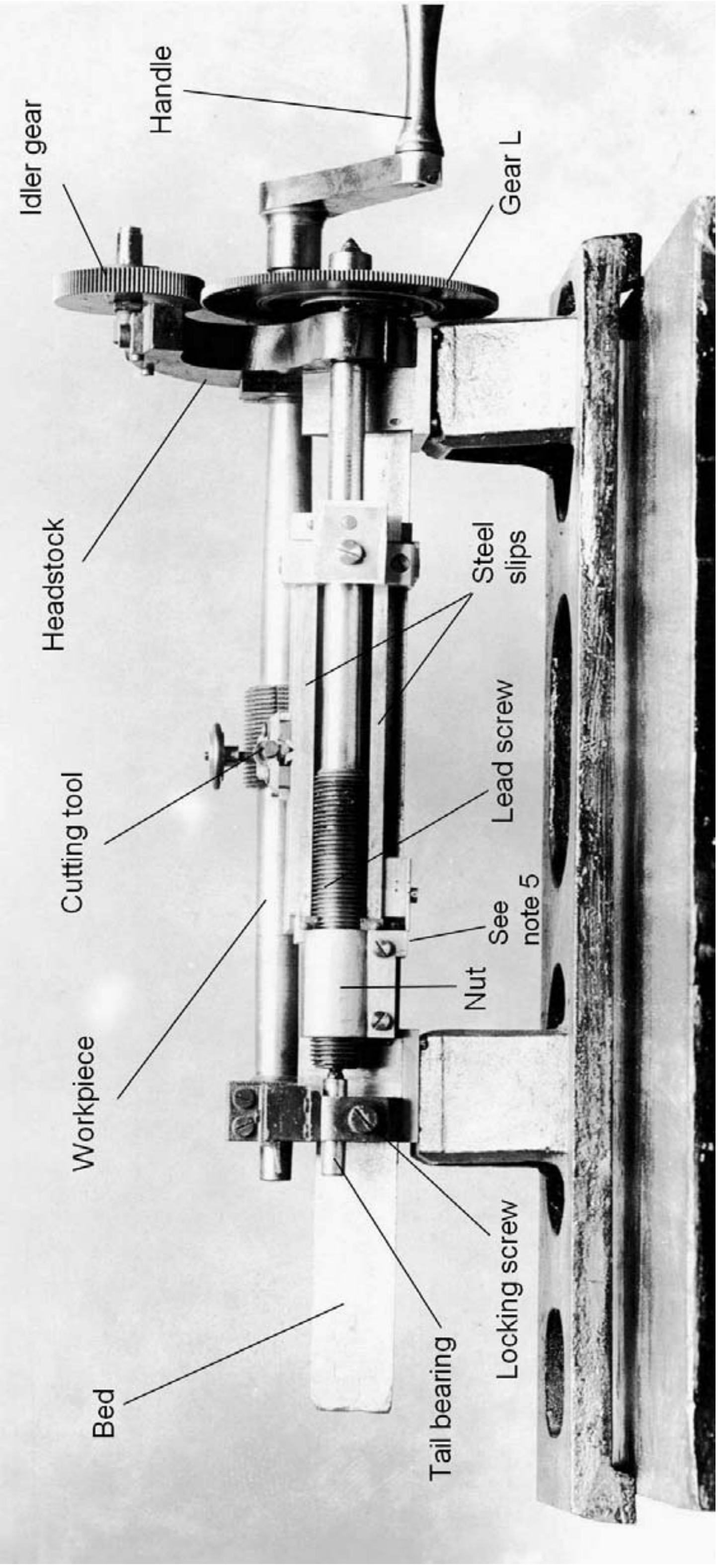

Figure 34
Ramsden’s screw-cutting lathe
Original photo courtesy of the Smithsonian Institution

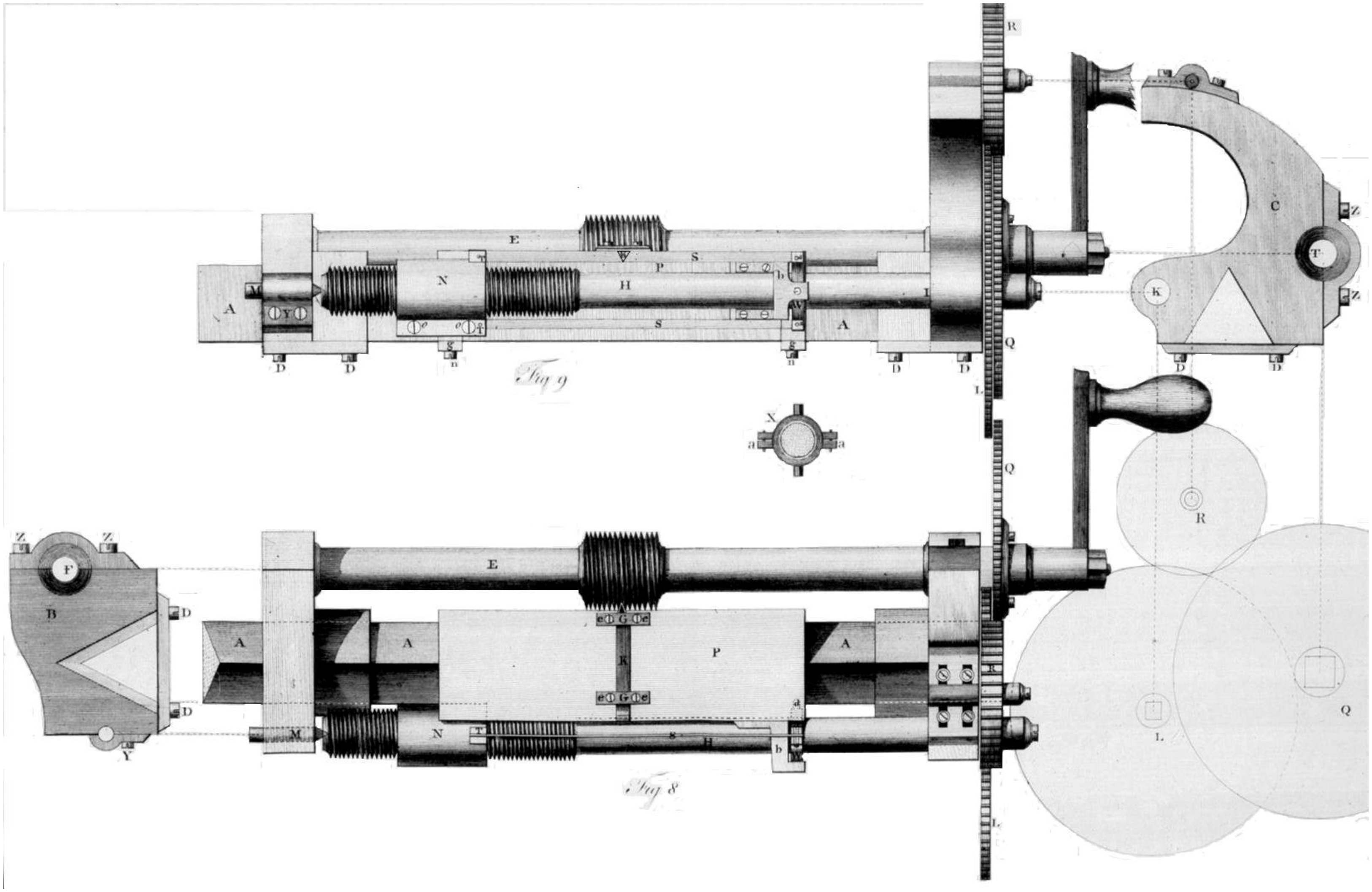

PLATE IV

TEXT page 13

a : *of its full dimensions…*
Scaling the drawing from the plan view of the dividing engine, the lathe bed would have been about 260 mm, say 10 inches, long and the diameter of the screw being cut about 26 mm, say 1 inch.

b : *a triangular bar of steel…*
This was probably forged from crucible steel made by the Huntsman process in Sheffield, the centre for British steel making from about 1740 onwards. It would have then been painstakingly filed into a bar with truly flat sides, of a constant angle to each other, possibly finished by lapping with an abrasive stone. Although in the 1830s Joseph Whitworth (1803 – 1887) popularised the method of trying three flat surfaces, one against the others in sequence, as a means of generating truly flat surfaces, the technique was probably a well-known craft skill long before. Whitworth, however, finished the surfaces by scraping, a technique he had probably learned from Henry Maudslay, for whom he worked for a time.

c : *after being hardened and tempered…*
The process has been briefly described above on page 9. Even when done carefully and especially if the steel blank is not homogenous, unpredictable strains in the material can be introduced by the hardening and tempering processes, which can introduce distortion when carried out after machining. Nowadays, parts that need to be hard are usually ground to a final finish, but Ramsden had to turn them on a lathe.

d : *to prevent it shaking…*
By this he means what we would now call end float or unwanted longitudinal movement, which would of course be fatal to the accuracy of the screw being cut.

e : …tightening the screws y…
These closed up the hole containing the cylindrical centre.

f : *a cylindric nut…*
This is a relatively long nut, enclosing about 20 threads, so that slight irregularities in pitch of the screw would tend to be averaged out. The “intelligent workman” would probably have known how to produce it, since Ramsden gives no hint. Producing internal threads of large diameter must have been a trial for an eighteenth century workman to whom a screw cutting lathe was not available. An internal chaser could have been used (Figure 35, next page), or the nut cast around the screw, but in this case the thread was most likely formed with a set of purpose-made taps that cut a progressively deeper thread until the final form was reached. Figure 36 shows three modern taps which cut progressively more from bottom to top, and, at the bottom, a hand-made tap used to initiate a coarse thread of special form in a nut.

It is also possible that a blank nut could have been lined with leather and squeezed around the screw to produce a screw of better regularity, first in brass and then in steel[22], so that a generation of screws, each better than its forerunner, would be produced.[23]

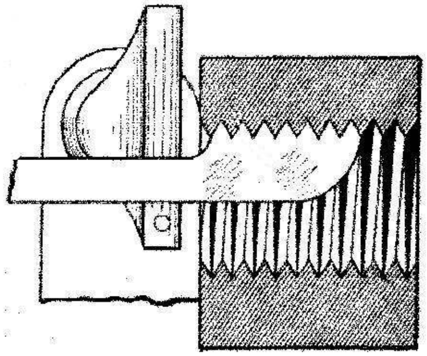

Fig 35 (After Holtzapfel)

Figure 36

Ramsden's drawing shows no way of preventing the nut from rotating anti-clockwise as the leadscrew is rotated, but in the photograph a tongue that extends beneath the bed can be seen beneath the right hand closing screw of the nut. Again, the intelligent workman would know that something of the sort had to be added to make the idea practical.

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[22] This technique was used at the National Physical Laboratory in the early years of the twentieth century when producing a generation of high-precision leadscrews, though pith was used instead of leather.

[23] In general, there is "degradation of accuracy", so that a screw produced by a machine tool is not as accurate as the tool's own leadscrew, for reasons explained in the introduction to this section.

g : *to prevent any shake,…*
Play here is unimportant so long as the nut is always moving in the same direction when a cut is being taken. Indeed, in Ramsden's lathe it *can* only be taken with the nut moving from right to left, as the force is transmitted to the carriage P via flexible steel strips S. In modern general purpose lathes too, successive cuts are always taken with the tool moving in the same direction, since it is not in practice feasible to remove all play between nut and leadscrew[24].

h : *intermediate universal joint W…*
It is not clear why this was used. Perhaps Ramsden was not confident that he could successfully attach a nut directly to the carriage at the correct distance and to ensure that the leadscrew was parallel to the motion of the carriage. Failure to meet both these conditions might deflect the carriage and its tool from the correct path.

TEXT page 14

a : The details are rather hard to see, so I have shown them in a high resolution copy with the parts arranged in a third angle projection, as Figure 37, next page. At the top right is the plan view and the other two views are what one would see standing to the front and left of the machine.

The cock, b, the supporting piece shaped somewhat like a reversed Z in plan view, is again not true to the drawing, but is made in two parts fastened together with a screw.

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[24] though modern ball screw systems can come close to doing so.

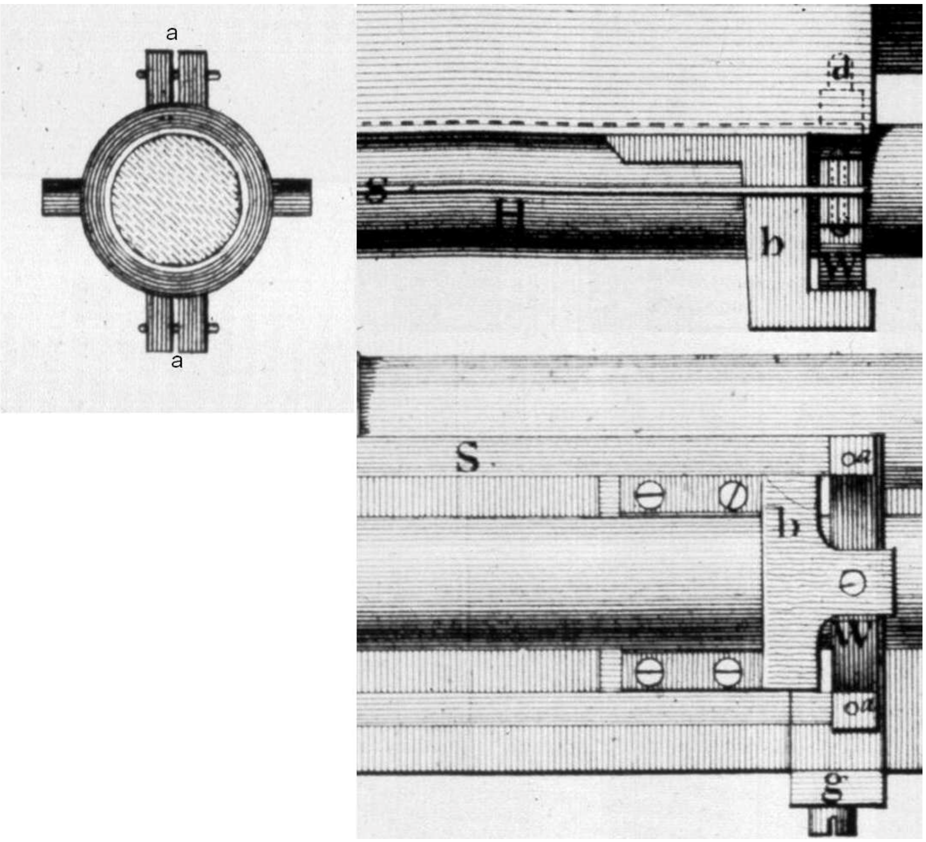

Figure 37

b : *bar of well-tempered steel…*
This is the cutting tool which, well-tempered or not, could not be expected to cut efficiently into the work-piece, also of hardened and tempered steel. When Ramsden came to cut a very similar screw for his "Engine for Dividing Strait Lines" he wrote in his account published two years later, in 1779 "*…:as it was necessary to cut the screw after the steel was hardened and tempered, therefore the tool was pointed with a diamond:...*"[25] Daumas says that this first engine also had a tool furnished with a diamond[26], but I have not found a source for this information. However, I have no difficulty in believing it.

c : *When the cutter is set to take proper hold… it may be fixed by tightening the screws…*
Even with the relatively fine pitch of the thread, it could not (and would not even nowadays) be cut in a single pass. The pitch is about 2 mm and the included angle of the thread appears to be about 30 degrees, so the total depth of cut would have been about 3.5 mm. In his longitudinal dividing engine he has shown

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[25] Ramsden, J.. *Description of an Engine for Dividing Strait Lines on Mathematical Instruments*. Commissioners of Longitude. London, 1779.

[26] Daumas, M. *Les Instruments Scientifiques aux XVII et XVIII siècles*. Paris, 1953. p.265

a feed screw and a separate locking screw, and a similar arrangement can be seen in the photograph of his actual lathe (Figure 38, below).

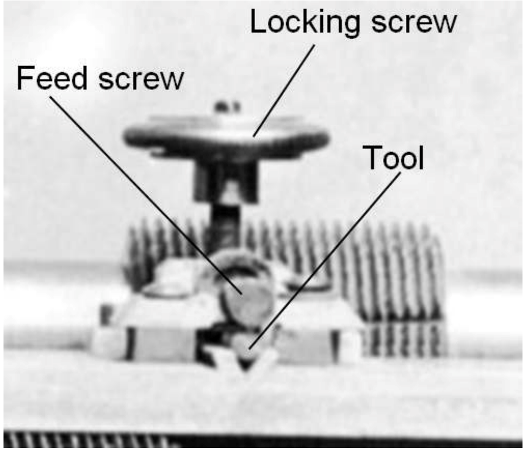

Figure 38

d : *the two screws in the same direction…*
Modern lathes have provision for inserting one or two idler wheels in the gear chain connecting the leadscrew with the driving spindle, so that left and right hand threads may be cut at will.

It is not clear why, having found that the pitch of the thread did not suit, he did not simply turn down the diameter of the worm wheel to suit. I suspect he had by this time removed it from the lathe and would not have been able to reattach it to the faceplate with the necessary accuracy of re-centring. Even today, it would be no easy task.

THE END.

PART III

AN ACCOUNT OF JESSE RAMSDEN[27]

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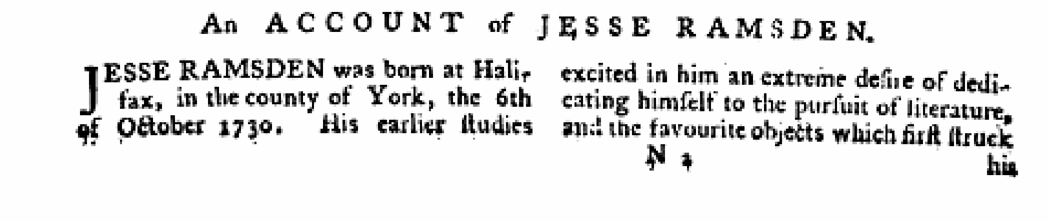
[27] from the European Magazine and London Review. February 1789, XV; 92 - 96



An ACCOUNT of JESSE RAMSDEN.

JESSE RAMSDEN was born at Halifax, in the county of York, the 6th of October 1730. His earlier ſtudies excited in him an extreme deſire of dedicating himſelf to the purſuit of literature, and the favourite objects which firſt ſtruck

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his

his youthful mind were hiſtory and antiquities. Mathematics and chemiſtry next engaged his attention; but his father, who was a clothier, preſſing him to follow ſome trade, he continued at home, in an employment not too well ſuited to him, till he was one-and-twenty.

At this period young Ramſden came to London in queſt of ſome occupation more worthy his genius. Amongſt other things, he applied himſelf to engraving, under the tuition of Burton. In this ſituation a fortunate circumſtance led him to the object for which Nature ſeems to have deſigned him—the improvement of aſtronomical inſtruments; for the invention and conſtruction of which he undoubtedly ranks the firſt in Europe. In the courſe of his employment, mathematical inſtruments were frequently brought to him to be engraved. The more he examined them the more he noticed their defects, and a ſecret inſtinct prompted him to wiſh to remove them. This wiſh was followed by a reſolution to attempt it. He ſoon made himſelf maſter of the file and the lathe, and even of working glaſſes; and in 1763 made inſtruments for Siſſon, Dollond, Nairne, Adams, and others. About 1768 he opened a ſhop for himſelf in the Haymarket *. At this period he formed the deſign of examining every aſtronomical inſtrument in uſe, in order to correct thoſe which, founded on good principles, were faulty only in their conſtruction, and to proſcribe thoſe which were defective in both points.

The reflecting quadrant, or ſextant of Hadley, ſo much uſed by Engliſh ſeamen, appeared to Mr. Ramſden the moſt uſeful inſtrument of its kind; but it was at this time extremely imperfect. The eſſential parts of it had not a ſufficient degree of ſolidity; the friction at the centre was too great, and in general the alidada might be moved ſeveral minutes without any change in the poſition of the mirror; the diviſions were commonly very inaccurate, and Mr Ramſden found that Abbé de la Caille did not exceed the truth in eſtimating at five minutes the error to which an obſerver was liable in taking the diſtance between the moon and a ſtar; an error capable of producing a miſtake of fifty leagues in the longitude. On this account Mr. Ramſden changed the principle of conſtruction of the centre, and made the inſtrument in ſuch a manner as never to give an error of more than half a minute; and he has now brought them to ſuch a degree of perfection as to warrant it not more than ſix ſeconds in a ſextant of fifteen inches. Since the time of having improved them, Mr. Ramſden has already † conſtructed 983; and in ſeveral which have been carried to the Eaſt Indies and America, the deficiency has been found no greater at their return than it had been determined by examinations before their being taken out. Mr. Ramſden has made them from fifteen inches to an inch and a half, in the latter of which the minutes are eaſily diſtinguiſhable; but he prefers for general uſe thoſe of ten inches, as being more eaſily handled than the greater, and at the ſame time capable of equal accuracy.

The invention of a machine for dividing mathematical inſtruments was requiſite, and to this Mr. Ramſden turned his thoughts with ſucceſs. Thoſe hitherto in uſe were very inaccurate. Graham and Bird uſed the dividers. The latter made a ſecret of his method: but before the Board of Longitude had purchaſed it, to make it public, Mr. Ramſden had invented for himſelf a method, and ſurpaſſed Bird in accuracy. For great works he ſtill uſes the dividers; but for common inſtruments they require too much time. He was ten years in bringing to perfection his engine, which unites the two properties of ſpeed and facility, and is no ſmall proof of the ſuperior talents of its inventor. With it a ſextant may be divided in the ſpace of twenty minutes; and for thoſe who may not chooſe to procure themſelves the engine, Mr. Ramſden engages to divide any ſextant for three ſhillings. This engine was laid before the Board of Longitude by Dr. Shepherd. A premium of ſix hundred guineas was given to the inventor by the Board; and a deſcription of the engine, with a plate of it, was publiſhed in 1777. This edition was burnt by accident, and we are informed, that M. de la Lande intends to have it reprinted, and a plate of the machine engraved, at Paris. The Board has frequently given greater premiums for inventions of leſs merit and utility: but the greateſt men do not always meet the greateſt rewards. Newton indeed was appointed Maſter of the Mint; but it is ſaid, that he was not indebted for this ſolely to his merit. Mr. Ramſden has

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* Ever ſince 1775 Mr. Ramſden has lived in Piccadilly.

† September 1, 1788.

alſo made an inſtrument for dividing right lines, a deſcription of which has been publiſhed.

Whilſt Mr. Ramſden was employed on his engine for dividing mathematical inſtruments, he alſo turned his attention to the improvement of various inſtruments which were capable of it. The theodolite was formerly nothing but a glaſs turning on a circle, divided into ſpaces of three minutes; but in the hands of Mr. Ramſden it is become a new and accurate inſtrument, equally uſeful for meaſuring heights and taking plans. The moſt admirable theodolite that has ever been conſtructed was made by him for Major-General Roy, for the purpoſe of meaſuring the ſeries of triangles in England, which were to form a connection with thoſe meaſured in France. Though this is only of eighteen inches radius, its accuracy is ſo great as not to admit an error of a ſingle ſecond. It has two glaſſes turning on an horizontal axis, with which may conſequently be meaſured the angles between objects of greater or leſs degrees of elevation, being brought to the horizon. The General has juſt meaſured the angle which the polar ſtar forms with the ſides of his triangles, in order to obtain the convergence of meridians as it actually is on the oblate ſpheroid of the earth. From theſe operations it is already ſhewn that the difference of meridians between the two obſervatories of Paris and Greenwich is 9′ 20″.

Mr. Ramſden has brought to remarkable perfection the barometer for meaſuring the heights of mountains. He has ſhewn M. de Luc, that it was the ſummit of the column of mercury, not the part in contact with the tube, the height of which ſhould be obſerved: this in his barometer may be aſcertained to the hundredth part of a line, and the elevation of a mountain determined to a foot nearly. He has engraved a table to accompany his barometers, which gives the height of a place from that of the inſtrument without the trouble of a calculation, and this for all the different degrees of temperature. He has alſo, in a moſt ingenious manner, reduced to the greateſt ſimplicity the apparatus for the conveyance and ſupport of this portable barometer.

Various inſtruments for philoſophical purpoſes have been executed by Mr. Ramſden, and all with ſome improvements. For inſtance: an electrical machine; a manometer for meaſuring the denſity of the air; an inſtrument for meaſuring an inacceſſible diſtance, which does not require the meaſuring a baſe; aſſay balances, which turn with the ten thouſandth part of the weight uſed; levels of an extreme ſenſibility; the dynameter, with which he meaſures the magnifying power of a lens; and to theſe might be added others, any one of which a common artiſt would think ſufficient to eſtabliſh his reputation, but of ſeveral of which Mr. Ramſden thinks ſo little as ſcarcely to ſeem conſcious that they deſerve notice.

The pyrometer for meaſuring the dilatation of bodies by heat has alſo employed the talents of Mr. Ramſden, as may be ſeen in the Philoſophical Tranſactions for 1785, and in the deſcription printed at Paris on account of the baſe meaſured for the triangles of Major-General Roy. That gentleman obſerved a grand defect in the pyrometers in uſe; that of the bodies employed in the experiment not being ſufficiently ſeparate. He has diſcovered a method of comparing, by means of his microſcopic pyrometer, a body expoſed to any degree of heat or cold with the ſame body in its natural ſtate; and by a micrometer adapted to the microſcope he meaſures the variations with a degree of accuracy hitherto unknown, and which has given the meaſure of a baſe with ten times as much preciſion as in any one that had before been meaſured. On this occaſion, as on all others, has Mr. Ramſden diſplayed that innate talent of diſcovering the eſſential defects of an inſtrument, and correcting them by the moſt certain and ſimple means, which nature muſt give, art can never acquire.

The ſcience of optics is not leſs indebted to him. He has acquired a new and accurate method of correcting the aberration of ſphericity and refrangibility in compound eye-glaſſes, applicable to all kinds of aſtronomical inſtruments. Opticians had imagined this purpoſe might be effected by making the image of the object fall between the two eye-glaſſes; but this was attended with great inconvenience, as the eye-glaſs could not be touched without affecting the value of the parts of the micrometer. To remedy this inconvenience, Mr. Ramſden ſet out with a very ſimple experiment, namely, that the borders of an image ſeen through a priſm are more faintly coloured in proportion as the image is nearer it. This led him to attempt placing the two eye-glaſſes between the eye and the image of the object, without omitting to correct the two aberrations, which he has accom-

pliſhed

pliſhed by placing the glaſſes in a manner altogether different from the common one, and altering the radii of the curves.

Mr. Ramſden has alſo invented a reflecting objective micrometer, which is deſcribed in the Tranſactions of the Royal Society for 1779. In this are pointed out the inconveniencies and inaccuracy of that firſt invented by Bouguer in 1748, in which the different poſitions of the eye with reſpect to the pencil of light, cauſe the two images to appear ſometimes to touch, at others to recede from each other, or both alternately by a kind of oſcillatory motion. He perceived alſo, that the aberration of the rays, which rendered the objects ill-defined, increaſed the inconvenience of that inſtrument. He thought it adviſeable therefore to ſubſtitute the principle of reflection to that of refraction. This inſtrument, not leſs ſimple than ingenious, contains no mirror or glaſs but thoſe neceſſary to the teleſcope; and the ſeparation of the two images depends ſolely on the inclination of the mirrors, not on the focus.

He has, however, turned his attention to the improvement of the refracting micrometer; and the fortunate idea of placing this micrometer preciſely in the conjugate focus of the firſt eye-glaſs, inſtead of on the ſide of the object-glaſs, ſuggeſted itſelf to his mind. By this means the contrary refractions of the two ſemi-lenſes, and of the whole lens, correct the error that takes place in the objective micrometer, in which the image depends only on the focus of the two ſemi-lenſes; and, the image being already conſiderably magnified before it falls on the micrometer, the refraction and imperfection of the glaſſes can occaſion no ſenſible error in the meaſure of the angles. It is true that the field of the micrometer muſt be leſs in this poſition than if it were near the object glaſs; but Mr. Ramſden has contrived to throw an uniform degree of light on the images in every part of the field. With this micrometer the diameters of planets may be meaſured in every direction:' it may be fitted to all kinds of acromatic glaſſes: it may be brought nearer to the object-glaſs, or carried farther from it, ſo as to render viſion diſtinct; and it may be withdrawn from the tube containing the eye-glaſſes, ſo as to uſe the teleſcope without the micrometer. All theſe advantages make Mr. Ramſden's micrometers highly valued, and the aſtronomer who has one of them may eſteem himſelf fortunate.

In 1786, Mr. Ramſden was choſen a Fellow of the Royal Society; an honour by no means unmerited, nor has it abated his ardour for his favourite purſuits.

The objects hitherto noticed have not been the moſt important of Mr. Ramſden's works. The tranſit inſtrument and the quadrant have received freſh improvements in his hands. The equatorial, firſt made by Siſſon and a little improved by Short, has been greatly improved by Mr. Ramſden. In the firſt place, he has rejected the endleſs ſcrew, which preſſing on the centre deſtroyed its accuracy; he has made the centre of the baſe the centre of gravity; he has contrived all the movements to take place in all directions; he has pointed out the means of rectifying the inſtrument in all its parts; and he has added to it a very ingenious little inſtrument for aſcertaining or correcting the effect of refraction. This invention was conſiderably prior to that which Mr. Dollond has given in the Philoſophical Tranſactions. Mr. Ramſden has procured a patent for his equatorial: but the beſt method of preventing others from imitating it would be to ſupply the demand for them by making a greater number himſelf. Mr. Mackenzie, brother to the Earl of Bute, a particular friend to Mr. Ramſden, has publiſhed a deſcription of this machine; but the inventive genius of Mr. Ramſden does not often ſuffer him to execute the ſame inſtrument many times in the ſame manner; and very frequently has he broken to pieces inſtruments, which, after having coſt a conſiderable ſum, have not ſucceeded to his wiſh.

The greateſt equatorial ever yet attempted is that which he is at preſent making for Sir William Shuckburgh, on which he has been employed theſe nine years. The circle of declinations is four feet in diameter, ſo that they may be obſerved nearly to a ſecond. The glaſs is placed between ſix pillars, which form the axis of the machine, and turn round by two pivots placed on two blocks of ſtone.

The tranſit inſtrument is uſed in all the great obſervatories of Europe, but Mr. Ramſden has made many improvements in it. He has invented a method of throwing light on the threads, by making it paſs along the axis of the inſtrument. The reflector is placed interiorly and obliquely in the middle; it takes nothing from the opening of the object-glaſs, and, as the light paſſes through a coloured priſm, which may be moved at will, it may be increaſed or diminiſhed.

For the verification of this eſſential inſtrument, Mr. Ramſden does not employ the ſpirit-level, which he does not very

highly

highly eſteem, as incapable of the accuracy he always aims at. His method is to ſuſpend a plumb-line before the glaſs placed vertically. This line paſſes through two points marked on two pieces fixed at the top and bottom of the glaſs, one of which is moveable in a ſmall degree. The line is quite detached from the glaſs, and when it anſwers to the ſame points in the two different ſituations of the glaſs, it is evident, that the axis is horizontal, as has been remarked by Mr. de la Lande, in his aſtronomy. But what is moſt new and ingenious in this method is, that the line ſometimes paſſes only through the images of the points, formed in the focus of a ſmall lens, becauſe he is occaſionally obliged to place the line at ſome diſtance from the inſtrument; but its accuracy is not diminiſhed, nor is there any parallax. "It is not the point I ſhall make uſe of," ſaid he once jocularly, "but its *ghoſt*."

The meridian glaſſes of Mr. Ramſden, ſuch as he has made for Blenheim, Manheim and Dublin, and ſuch as he is making for Paris and Gotha, are remarkable for the excellence of their object-glaſſes. With that at Dublin, Mr. Uſher obſerved ſtars of the fourth magnitude at mid-day, and thoſe of the third very nearly in conjunction with the ſun. Theſe glaſſes are eight feet in length.

The mural quadrant is the moſt important inſtrument uſed in aſtronomy; and in this Mr. Ramſden has diſtinguiſhed himſelf by the accuracy of his diviſions, and by the manner in which he finiſhes the planes by working them in a vertical poſition. He places the plumb-line behind the inſtrument, that there may be no neceſſity for removing it when we take an obſervation near the zenith. His manner of ſuſpending the glaſs, and that of throwing light on the object-glaſs and on the diviſions at the ſame time, are new, and improvements that deſerve to be noticed. Thoſe of eight feet which he has made for the obſervatories of Padua and Vilna, have been examined by Mr. Maſkelyne: the greateſt error does not exceed two ſeconds and a half. That of the ſame ſize for the obſervatory of Milan is in a very advanced ſtate.

The mural quadrant, of ſix feet, at Blenheim is a moſt admirable inſtrument. It is fixed to four pillars, which turn on two pivots, ſo that it may be put to the north and to the ſouth in one minute. No one could be more worthy of poſſeſſing ſo beautiful and perfect an inſtrument than the Duke of Marlborough, whom no aſtronomer by profeſſion excels in zeal, aſſiduity, or accuracy. It was for this inſtrument Mr. Ramſden invented a method of rectifying the arc of ninety degrees, on which an able Aſtronomer had ſtarted ſome difficulties; but by means of an horizontal line and a plumb-line, forming a kind of croſs, without touching the circle, he ſhewed him, that there was not an error of a ſingle ſecond in the ninety degrees; and that the difference was occaſioned by a mural quadrant of Bird, in which the arc of ninety degrees was too great by ſeveral ſeconds, and which had never been rectified by ſo nice a method as that of Mr. Ramſden.

But the quadrant is not the inſtrument which ſtands higheſt in Mr. Ramſden's opinion; it is the complete circle: and he has demonſtrated to M. de la Lande, that the former muſt be laid aſide, if we would arrive at the utmoſt exactneſs of which an obſervation is capable. His principal reaſons are: 1ſt, The leaſt variation in the centre is perceived by the two diametrically oppoſite points. 2dly, The circle being worked on the turn, the ſurface is always of the greateſt accuracy, which it is impoſſible to obtain in the quadrant. 3dly, We may always have two meaſures of the ſame arc, which will ſerve for the verification of each other. 4thly, The firſt point of the diviſion may be verified every day with the utmoſt facility. 5thly, The dilatation of the metal is uniform, and cannot produce any error. 6thly, This inſtrument is a meridian glaſs at the ſame time. 7thly, It alſo becomes a moveable azimuth circle by adding an horizontal circle beneath its axis, and then gives the refractions independent of the menſuration of time.

Mr. Ramſden is juſt finiſhing a circle of five feet for the Obſervatory at Palermo. He then deſigns to execute one for the Obſervatory at Paris, for which he has received the moſt preſſing ſolicitations from M. de la Lande. He then hopes to finiſh that for Dublin, which is already very forward, and is of twelve feet. One of ſeven or eight feet, however, is ſufficient to obtain an exactneſs to half a ſecond, as in the zenith ſector uſed for the niceſt obſervations of the figure of the earth.

Every one who has ſeen it muſt have remarked with great ſatisfaction the ingenious manner in which the axis is ſupported, preventing the friction of the pivots; and particularly the new invention of Mr. Ramſden for rendering the axis

axis perfectly horizontal, by means of a plumb-line which is ſituated without the machine: his inventive genius has exerciſed itſelf on this new problem, and ſolved it in the completeſt manner.

That every part of his inſtruments may be fabricated under his own inſpection, Mr. Ramſden has in his workſhops men of every branch of trade neceſſary for completing them. Each man is conſtantly employed on the ſame work, and thus arrives at the greateſt nicety in executing it; yet, notwithſtanding its perfection, which ought to enhance the profits of the artiſt, Mr. Ramſden ſells his inſtruments at a leſs price than any other perſon in London, ſometimes even one-third lower. Though he has near ſixty men conſtantly employed in his workſhops, it is not poſſible for him to ſupply readily the demands he has from all parts of the world: this many foreigners have experienced in the difficulty of procuring his inſtruments.

No one can be more diligent, or leſs eager in the purſuit of wealth or pleaſure, than Mr. Ramſden. He is extremely frugal, and, unleſs vexed, civil, complaiſant, and affable, in a high degree. Loved and eſteemed amongſt his intimates at home, his talents have not failed to procure him abroad that reputation which he ſo juſtly deſerves.

For the EUROPEAN MAGAZINE.