Vistas in Astronomy, 1976, Vol. 20, pp. 123-130. Pergamon Press. Printed in Great Britain

18. THE INFLUENCE OF THE ROYAL OBSERVATORY AT GREENWICH UPON THE DESIGN OF 17th and 18th CENTURY ANGLE-MEASURING INSTRUMENTS AT SEA

A. STIMSON

National Maritime Museum

When Charles II founded his Royal Observatory in Greenwich Park in 1675, position finding at sea was not much advanced on the techniques of 200 years earlier when the Portuguese began the art of ocean navigation. It was possible to find a ship's latitude reasonably easily to within 20 or 30 minutes but the business of finding longitude still seemed an insoluble problem. The answer was thought to lie in the lunar-distance method put forward by Werner in 1514, but for this method to be successful, not only was it necessary for the Moon's position to be predicted to within 1 minute of arc several years in advance, but also the "fixed" stars upon which the method depended had to be observed to a like accuracy.

Greenwich Observatory was established with the object of finding a solution to the longitude problem, but of necessity Flamsteed concentrated his early efforts on the accurate observation and plotting of star positions.

The alternative means of solving the longitude question was the "meckanick's" answer, a clock that would keep time under seagoing conditions and temperatures. In this way a Standard Time could be carried about with which to compare the ship's local time — the difference in time being the longitude.

It is not generally realized that neither of these methods could be of much use to a seaman unless he were equipped with a sufficiently accurate instrument with which to observe the exacting measurements required.

The Lunar-distance method required distances between the Moon and Sun or a star to be observed, as well as the altitudes of the bodies concerned, before the computation could begin. The chronometer method needed an accurate instrument for an altitude sight to determine local time to be taken when the Sun was moving at its most rapid rate near the Prime Vertical.

No instrument of this capacity existed when the Greenwich Observatory was founded in 1675, for British seamen were still using the backstaff, invented by Captain John Davis about 1594, and the cross staff, first used at sea about 1510. Neither of these instruments was capable of consistently measuring a celestial angle to an accuracy of ± 10 minutes of arc due to inherent defects in their design, though their scales were graduated to 90° with a theoretical accuracy of 1 minute of arc.

THE CROSS STAFF

The cross staff, or forestaff as it was sometimes called from the posture of the observer who faced the thing observed, consisted of a squared wooden staff about 30 inches long, each side being graduated unequally like a scale of tangents. To each scale there was a transversal or cross which fitted onto the staff and could be slid up or down it. They were known as the 10, 30, 60 and 90 [degree] crosses.

To observe the altitude of the Sun at noon, the navigator selected the appropriate cross for the expected altitude and placed it on the staff. He then put the flat end of the staff close to his eye and either moved the cross away from, or towards himself, until the lower end of the cross was just in line with the horizon and the upper end of the cross cut the centre of the Sun. This last operation was damaging to the eye, so that it was customary either to fit a dark glass to that end of the cross, or for the observer to cover the Sun completely with the end of the cross and measure the upper limb, subtracting 16' from the measured altitude. The altitude was read off where the cross cut the scale at the moment the Sun ceased to climb, and a simple addition and subtraction calculation gave the latitude.

Ignoring the fact that wood will warp in the best of climates, and the effect of parallax when the end of the staff is not placed in exactly the right position by the eye, there was still another problem, ably expressed by William Bourne writing in 1574.

> ... but if it [the altitude] doe exceed 50 degrees then by the means of casting your eye upwardes and downwardes so muche, you may soone commit error, and then in like manner the degrees be so small marked, that if the Sunne dothe passe 50 or 60 degrees in height, you must leave the cross staffe and use the Mariner's Ring, called by them the Astrolaby which they ought to call the Astrolabe".[1]

The mariner's astrolabe was first used in the last quarter of the 15th century and measured angles to the nearest half degree.

Despite its shortcomings, the cross staff was the only instrument capable of being used to measure a star's altitude, usually the Pole Star's at sea, and its maximum practical measuring ability was about 50° or 60°.

THE BACKSTAFF

The backstaff was developed out of the cross staff by Captain John Davis, and relied on the shadow cast by the Sun. The observer stood with his back to the Sun, (hence "backstaff"), using the horizon directly opposite it.

The instrument was again wood framed, usually in lignum vitae, and consisted of a staff about 26 inches long to which were attached two boxwood arcs, whose radii were struck from the same centre at the horizon end of the staff and whose sum made 90°. The lesser arc was graduated to 60° and the larger to 30° although towards the end of its use these became 55° and 35°.

The backstaff's main advantage over the cross staff when observing noon altitudes for latitude was that the 30° arc was divided with a diagonal scale so that it was theoretically possible to measure angles down to 1' of arc. In practice accuracy fell far short of this.

The observer placed three vanes upon his instrument; the sight vane on the large arc, the shadow vane on the small arc and the horizon vane on the end of the staff. Placing the shadow vane at an angle less than the expected altitude he moved the sight vane either up or down the large arc until he could see the horizon through a slit in the horizon vane while at the same time the upper edge of the shadow cast by the shade vane fell across the horizon slit. He had to maintain this position until the Sun ceased to climb, despite the movement of the ship, and add the sum of the two arcs together in order to obtain his latitude. In hazy weather, of course, the Sun cast very little shadow, or none at all, and there was always the blurred edge of the shadow to make the observation more difficult.

Ocean navigation at this time consisted, in the main, of sailing well to seaward of a desired landfall of known latitude, observing the Sun or Pole Star with one or other of the two instruments just described to find the ship's latitude, and then running down the latitude to the landfall.

There was no observational check on distance run in an East or West direction and disasters frequently occurred when the land was found unexpectedly soon or, in the case of an island landfall, missed altogether. In an age when measurement was still an inexact science and geographical knowledge and cartography left a lot to be desired it is no wonder that Charles Leigh describing his improved backstaff in *the Philosophical Transactions of the Royal Society* in 1737, could say

> The Sea Quadrant now in use, called, Captain Davis's Quadrant being invented by that ingenious Gentleman for taking the Sun's Altitude is an instrument universally approved and sufficiently accurate. I say sufficiently because it is well known to all Artists at Sea that five or ten Minutes Error (which is generally the most, if the instrument be good, though the motion be great) is a Trifle scarce worth the noting, either in sailing near a Meridian or Parallel Circle.[2]

There was no point in being ultra-accurate in observation if the current charts were not similarly accurate, and this would not be possible until a way of finding longitude at sea was discovered.

However, improvements to instruments were continually being suggested and one of the most successful to both the cross staff and the backstaff was Flamsteed's lens. This invention is described in Sir Jonas Moore's *New System of Mathematicks,* 1681, which was part written by and edited largely by the Reverend John Flamsteed, the first Astronomer Royal, upon the death, in 1679, of his patron.

It is described in the following manner,

> Of late there has been used a lens or double convex-glass, fixt in the Shade Vane, which contracts the rays and casts them in a small bright spot on the slit of the Horizon-Vane instead of the shade, which has much improved the instrument if the glass be well and truly fixt: for now it may be used in hazie weather and that so thick an haze that an Observation can hardly be made with the Fore-staff, also in clear weather the spot is more defined and conspicuous than the shadow, which at best is not terminated. This was the contrivance of Ingenious Mr Flamsteed.[3]

Flamsteed's lens is often found on surviving backstaves which still have their original vanes and was obviously a popular improvement that met with the seaman's approbation.

THE REFLECTING INSTRUMENTS

Shortly after the founding of the Observatory, the British Parliament passed an Act offering a £20,000 reward for a practical means of finding longitude at Sea. This, coupled with Britain's expanding commercialism at home and overseas, provided the necessary impetus for new designs of instruments and the eventual solving of the longitude problem with the publishing of the *Nautical Almanac* for 1767 and the winning of the longitude prize by John Harrison with his timekeeper, H.4, in the same decade.

During the summer of 1730 John Hadley, F.R.S. invented the single most important improvement to the seaman's celestial measuring capability in his reflecting octant. He described to the Royal Society on 13th May 1731, two forms of the instrument, the mathematical principles, and their fitness for use at sea. Hadley was confident that when the theory of lunar prediction was perfected his

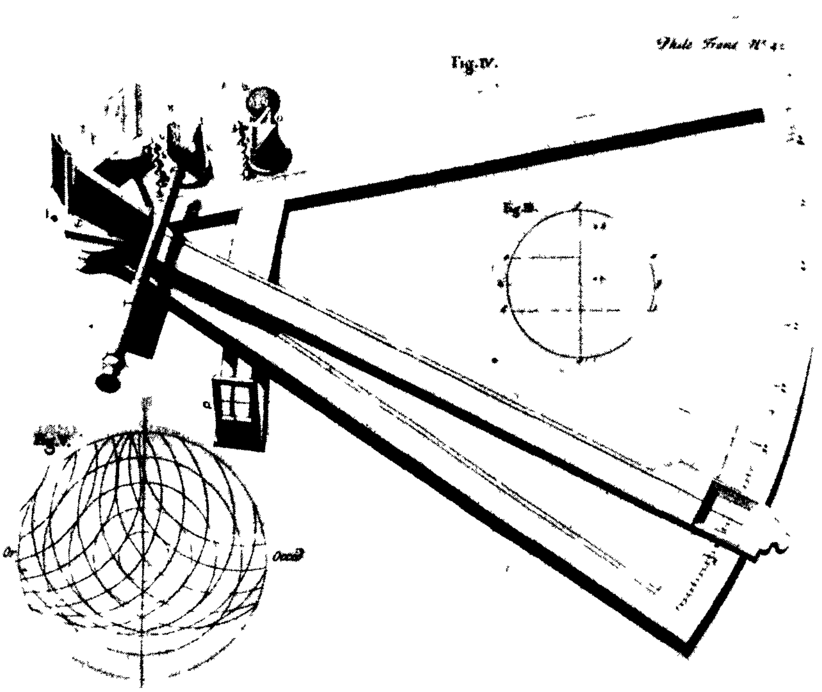


Fig. 18.1. John Hadley's second reflecting octant (quadrant) as illustrated in the *Philosophical Transactions of the Royal Society No. 420, 1731.*

quadrant could be used to measure the necessary lunar distances required to find longitude at sea. In fact he concluded with the statement

> How far an instrument of this kind may be of use at Sea to take the Distance of the Moon's Limb from the Sun or a Star in order to find the Ships Longitude, when the Theory of that Planet is perfected, I leave to Trials to determine.[4]

The reflecting octant enabled latitude to be observed with unprecedented accuracy at sea and also the altitude of the Sun with sufficient accuracy for the local time to be determined on board ship — both prerequisites to determining longitude. An additional advantage of Hadley's octant was that, for the first time, it was possible to adjust the observing instrument and so eliminate most of the errors due to warping of its frame or rough handling, before each observation. Since Hadley's instrument measured up to one quarter of a circle (a quadrant or 90 degrees) on the principle of double reflection, the actual arc of the instrument was only one eighth of a circle; it should in consequence be called an octant, but British seamen generally referred to it as Hadley's quadrant. (Fig. 18.2).

For observing altitudes the octant was held with the arc in the vertical plane and by moving the index arm away from the observer it was now possible to sight and measure the angle between two objects by bringing the reflection of one into coincidence with the sighted image of the other in the horizon mirror and to maintain it irrespective of the motion of a ship.

In 1732 the octant was tested by the Admiralty aboard the yacht *Chatham* where it performed remarkably well. The encouragement and interest which made these trials possible was supplied by Dr. Edmond Halley F.R.S. the Astronomer Royal and Mr James Bradley, F.R.S., his successor in the post. Bradley actually took part in the trials in *Chatham*.[5] Hadley patented his invention in 1734 but did not manufacture the instrument himself, preferring to leave this to established instrument makers such as Joseph Jackson, Jeremiah Sisson and John Bird.

Although a tremendous improvement over the backstaff and the cross staff for measuring altitudes of the Sun or a star when finding latitude at sea, it was nearly 20 years before the Hadley octant came into general use. This is not surprising when it is realized that a seaman had to provide his own instruments so that he generally preferred the cheaper backstaff to an expensive "new-fangled" device that needed constant adjustment. John Leigh summed it up in 1737 in a letter to the Royal Society when he says

> "... long use of this instrument [the backstaff 1 has, to my knowledge, (having had 17 years in the Royal Navy) occassioned such a fondness to it, that it would be no easy matter to dissuade the Navigator from the use of it to any other."[6]

In 1747, Captain, later Admiral John Campbell (1720?-1790) tested the suitability of Hadley's octant for taking lunar distances at sea, a subject in which he had a keen interest because he had sailed with Anson in the *Centurion* during his circumnavigation of the world in 1740—1744 and had witnessed the desperate search for the island of Juan Fernandez in the Pacific. Their long search for this island was a direct result of not knowing their longitude.

When in 1755 Tobias Mayer sent his lunar prediction tables to England to be considered for the Longitude Prize, (his widow was eventually paid £3000) Campbell was again ordered by the Board of Longitude to try the new tables and also the circular reflecting instrument Mayer had designed. Mayer's reflecting circle was designed to eliminate some of the inaccuracies found in Hadley's quadrant, such as centring error and errors in the graduation of the scale, by multiple readings over a circular scale and also to be capable of measuring angles of 120° which are sometimes necessary when observing lunar distances. John Bird, the London instrument maker, had made such an instrument to Mayer's design of 16 inches diameter, but Campbell's unfavourable opinion of it resulted in him asking Bird to make him a Hadley quadrant with the scale extended to measure angles of 120 degrees — a sextant. John Bird's sextant, made to astronomical standards, had a radius of 16 inches, twice that of the circle, so that its scale accuracy was adequate for lunar distance observations. Also, its greater handiness, smaller size and lighter weight made it more use aboard ship.

Nevil Maskelyne was sent to St. Helena in 1761 to observe the transit of Venus, taking with him probably the second sextant made by John Bird, so that he could observe lunar distances to determine the longitude from "time to time". In a letter to the Secretary of the Royal Society dated September 9th 1761 he described in detail the construction of this instrument. It was of 20 inch radius with an arc and index made of brass and the frame of well-seasoned mahogany. The mirrors and shades were specially made by Peter Dollond, the acknowledged expert in optics at this time. The vernier read down to 1 minute of arc and the index given a slow motion by means of a tangent screw. Maskelyne's instrument was also fitted with a 6-inch telescope with a magnifying power of 4 times.[7]

The tangent screw is interesting because it consisted of a plate which could be screwed down to the scale containing the head of the screw, by turning of which the index was carried backwards and forwards "at pleasure". Now Bird had made the 8-foot brass mural quadrant for Greenwich Observatory in 1750, (a copy of Graham's iron quadrant of 1725) and both these instruments had a similar type of slow motion screw. Bird was still using this rather clumsy device on his sextants in 1769 when he supplied James Cook with an instrument for his first voyage of discovery.

Maskelyne had proved the feasibility of the lunar-distance method — and of Bird's sextant — at sea but realized the length of the computation, some 4 hours, put the method beyond the powers of ordinary navigators. He attempted to rectify this by publishing his *The British Mariners' Guide* in 1763 where he explained his method and the computation. However it was not until *The Nautical Almanac* and the *Requisite Tables* were published for 1767, based on Mayer's revised tables sent by his widow in 1763, that the method became practicable for seamen in general.

Maskelyne maintained his interest in the practicability of the lunar method and corresponded with practical navigators - for example the letter published in the *Philosophical Transactions* dated 13 December 1764 in which Mr John Horsley, Fourth Mate on board the East India ship *Glatton,* gives an account of his efforts with a Bird instrument and Maskelyne's *British Mariner's Guide,*

In a social climate where artisans and scientists were both fellows of the same scientific society, an easy exchange of ideas was possible and Maskelyne appears to have been on good terms with Peter Dollond, the son of John, and an equally famous London instrument maker and optician. In fact Dollond wrote an open letter to Maskelyne in 1772 describing improvements to Hadley's quadrant by means of which the back horizon glass might be more truly adjusted. Dollond felt that the quadrant would then be more suitable for lunar distances as it would be reliably capable of measuring angles in excess of 90° by means of the back horizon fittings. He was mistaken in this, but went on to say "To these improvements, Sir I have added your method of placing darkening glasses behind the horizon glasses, which you have been so kind as to give me the liberty to apply to my instruments".[8]

The improvements alluded to were milled-head screws passing through the frame by means of which the horizon glasses could be adjusted perpendicular to the plane of the instrument and what in modern parlance would be termed the horizon-glass shades. Obviously Maskelyne's practical experience at sea coupled with his astronomical observing had suggested these improvements to him.

Maskelyne went on to publish some *Remarks on the Hadley's Quadrant* in the edition of the *Nautical Almanac* for 1774 (which was published in 1772) in which he explained the importance of parallelism of the planes of both sides of the index and horizon glasses and the equally important reasons for ensuring that the telescope was parallel to the plane of the instrument.

Maskelyne's explanation of the first problem was expressed in the following way:

> ... if the upper part of the index-glass be left unsilvered on the back and made rough and blackened, the lower part of the glass being silvered as usual, which must be covered whenever any celestial observations are made .... Then, if the telescope be sufficiently raised above the plane of the quadrant, it is evident that the observations will be made by rays reflected from the fore surface of the upper part of the index glass, the observations will be true whether the sub-surfaces of the glass are parallel planes or not.[9]

Maskelyne also went on to discuss the sizes of glass to use, the silvering of them and the height of telescopes. Telescopes that raise and lower are standard fittings on most sextants today, but Maskelyne's half-silvered half-roughened index glass with its covering flap is to be found on only a very few early 18th-century sextants.

The success of James Cook's three voyages between 1769 and 1781, when both the lunar-distance method and the chronometers proved capable of finally solving the longitude problem, encouraged ordinary navigators to attempt the new methods, so that an increasing demand for the sextant was created.

Navigational sextants were at first large, of 20-inch radius and heavy in use, requiring a pole to support their weight, but after Jesse Ramsden had in 1771 invented his dividing engine to engrave scales mechanically, their size was much reduced. By 1780 the average sextant was about 14 inches in radius and rigidly constructed from thick brass struts, although cheaper wooden-framed instruments were also available. In 1788 Edward Troughton patented his pillar-framed sextant composed of double flat bars connected by pillars. This proved as strong but much lighter and was copied by all the best instrument makers, remaining popular into the twentieth century.

Many other improvements to frame design, mirror mounting and adjustment, and tangent screw were evolved during the 18th and 19th centuries with the micrometer-drum tangent screw for moving the index arm being the most important. Micrometer tangent screws had been fitted to astronomical instruments since the 17th century but its first application to a sextant appears to be on a Ramsden instrument of c. 1780 (Fig. 18.3) although they did not come into general use until about 1920.

Just how many sextants were in use in these early days is difficult to determine but some idea of the quantities produced can be gauged from a study of the manufacturer's serial numbers when stamped upon their product. Not many 18th-century instrument makers did this, but the two firms that I have records for, Jesse Ramsden and his successors and the Troughton business, produce some interesting facts. The difficulty in this study is correlating the serial number on an instrument to a specific date. Octants before 1800 were frequently inscribed with the owner's name and date of manufacture, but such inscriptions are rarely found on sextants. Documentary evidence has produced other correlations, and interpolation between serial numbers when the business changed hands has produced others. The result is a graph (Fig. 18.4) which on the evidence available enables the date of a sextant or reflecting circle produced by those makers named to be estimated within a year or two. It also enables the quantities of instruments produced to be evaluated for a specific number of years thus:

Ramsden's total sextant production for the period cl760 to 1800 is within ± 10 of 1450 sextants, or on average thirty-eight per year. For the period 1780 to 1800 the average increases to nearly forty-three per annum. The same production figure for sextants was achieved by the Troughton firm between 1790 to 1800, although Troughton's newly-invented reflecting circle (1796) did not do nearly so well, the sale of circles falling off drastically after 1810.

Among anomalies brought to light are that the Ramsden sextant *No.932,* issued by the Board of Longitude to Matthew Flinders in 1801, was a 13- year-old instrument and not bought new. Also a sextant in private hands in Paris signed *Berge, late Ramsden* and serial numbered 1352 was in fact made about 1797 by Ramsden. A closer inspection of the signature reveals that *Berge, late* is inscribed by a different hand at a later date; presumably the sextant was old stock taken over by Matthew Berge in 1800 when Ramsden died.

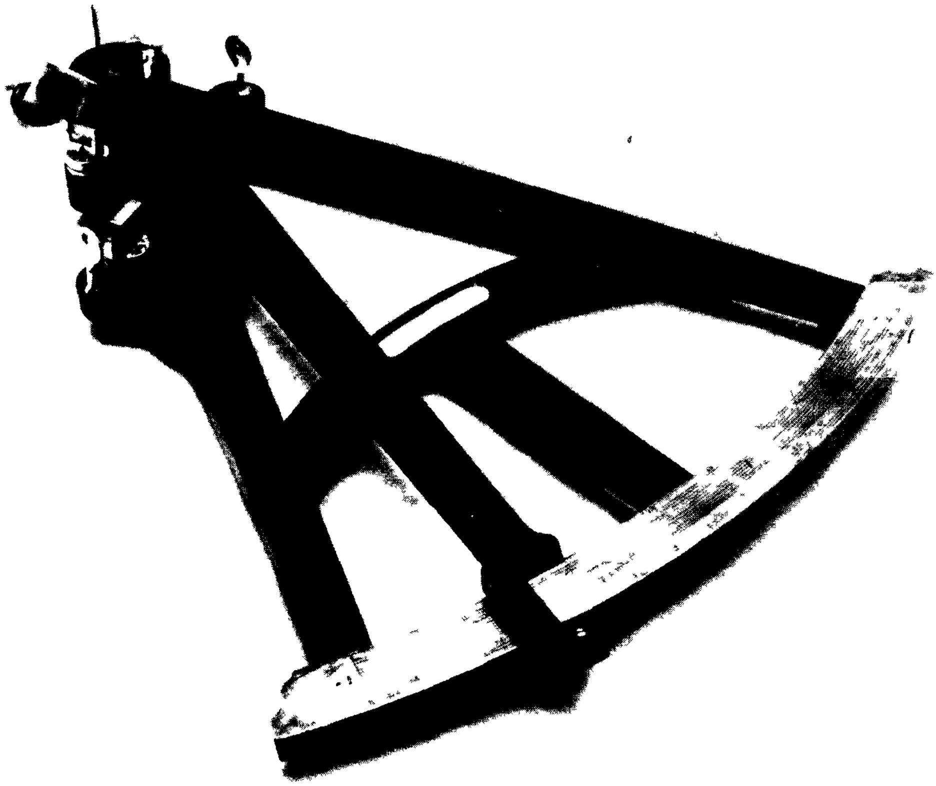
Evidence so far points to Berge, and later Worthington & Allan, continuing the sequence of these serial numbers as the business changed hands and indicates a decline in sales as the Ramsden reputation faded into the past. An awkward fact that apparently has no answer is that Ramsden did not actually stamp his sextants with a serial number until the early 1780's, although he certainly kept a tally. The earliest recorded serial number to date is No. 724 and several early examples of Ramsden's sextants have come to light bearing no number at all. These are presumably prior to 1780. Ramsden's undoubted superiority in sextant-scale engraving was based upon the dividing engine he developed between 1771 and 1773, the secrets of which he divulged to the Board of Longitude for the sum of £615.

Ramsden divided scales for other makers for a fee and is said to have been able to divide an octant scale in 20 minutes.

Evidence of this specialist work for other makers is found in the scale stamp used by Ramsden, (Fig. 18.5) and later other specialists, on instruments bearing the name of other makers. The foul anchor with the initial letters 'I.R.' on either side have been found on a Benjamin Martin octant of c.1775, a Nairne and Blunt sextant of c.1780 and was still being used by Worthington on a sextant of c.1835. The practice seems to have practically died out by 1800 on sextants but firms like Spencer Browning & Rust and Dring & Fage were still stamping octant scales with their monograms into the 1840s.

An attempt to calculate the demand for sextants and thereby the number of navigators involved in using lunar distances at sea must of necessity be only slightly better than a guess.

In 1800 there were probably only eight to ten instrument makers actually producing sextants of the ninety or so makers listed in the London trade directories.[10]



Fig, 18.2. A 20-inch Hadley octant signed *Geo Adams Londini fecit 1753.* The earliest dated octant in **the** National Maritime Museum collection. NMM reference; *S.I 01.*

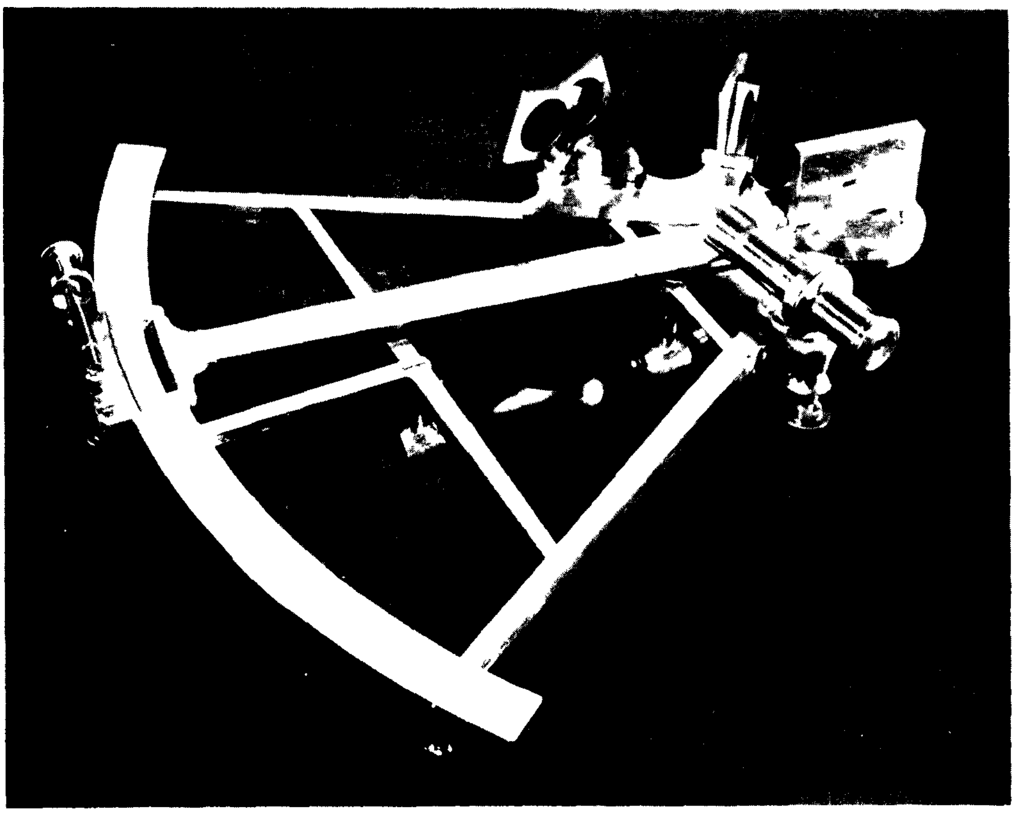
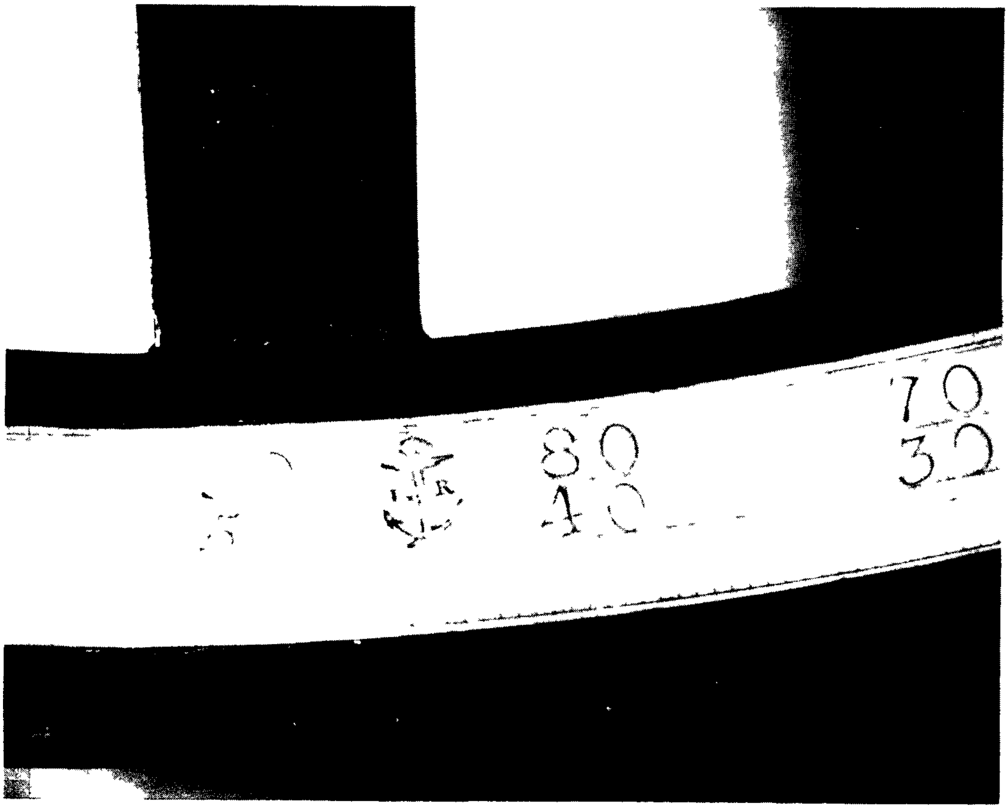


Fig. 18.3. A 12-inch sextant signed *Ramsden London,* serial numbered 724, c.1783. This sextant is fitted with the earliest known micrometer drum. NMM reference S 27.



Pig. 18.5. Jesse Ramsden's dividing stamp on the scale of a wooden sextant by Worthington, c.1835.

Of these eight to ten, only the workshops of Ramsden, Troughton and Dollond produced them at the rate of forty sextants per year. Taking the production rate as thirty sextants per year for ten instrument-making firms, a grand total of 300 sextants could have been available for sale in London each year to satisfy demand at home and abroad.

This figure may be too high by at least one third but, even when allowance is made for the fact that many sextants went to astronomers, surveyors, and hydrographers, about 150 to 200 sextants of all types were probably being sold to seamen in London annually.

This, coupled with the fact that by 1800 Ramsden had sold about 1450 sextants and Troughton about 480 sextants and 50 circles does highlight the success of the *Nautical Almanac* and both methods of finding longitude at sea, made possible by the painstaking work and perserverance of successive Astronomers Royal and their contact with the scientific world around them in the 17th and 18th centuries.

REFERENCES

1. William Bourne, *A Regiment for the Sea,* 1574,
2. Charles Leigh, "A description of a Water level to be fixed to Davis's Quadrant..." *Phil, Trans.* No. 451 1738 p. 413.
3. Sir Jonas Moore, *A Neva System of Mathematicks,* 1681. p. 250.
4. John Hadley, "The Description of a New Instrument for taking Angles" *Phil. Trans,* No. 420, 1731. pp.147-157.
5. John Hadley, "An Account of Observations made on board the Chatham Yacht..." *Phil Trans.* No. 425, 1732. pp. 341-356.
6. Charles Leigh. ***op.cit.***
7. Nevil Maskelyne, "A Letter from the Rev. Nevil Maskelyne, M.A. **F.R.S.** to the Rev. Thomas Birch, D.D, Secretary to the Royal Society: containing the Results of Observations ..." *Phil. Trans.* Vol. LII, Part 1 1761. pp. 558-563.
8. Peter Dollond. "A letter from Mr Peter Dollond to Nevil Maskelyne F.R.S. and Astronomer Royal; describing some Additions and Alterations made to Hadley's Quadrant to render it more serviceable at sea ..." *Phil. Trans.* Vol. LXII 1772.
9. Nevil Maskelyne. "Remarks on the Hadley's Quadrant". *Nautical Almanac* 1774 pp. 57-59.
10. E.G.R. Taylor. *The Mathematical Practitioners of Hanovanan England 1714-1840, 1966* pp. 328-379.

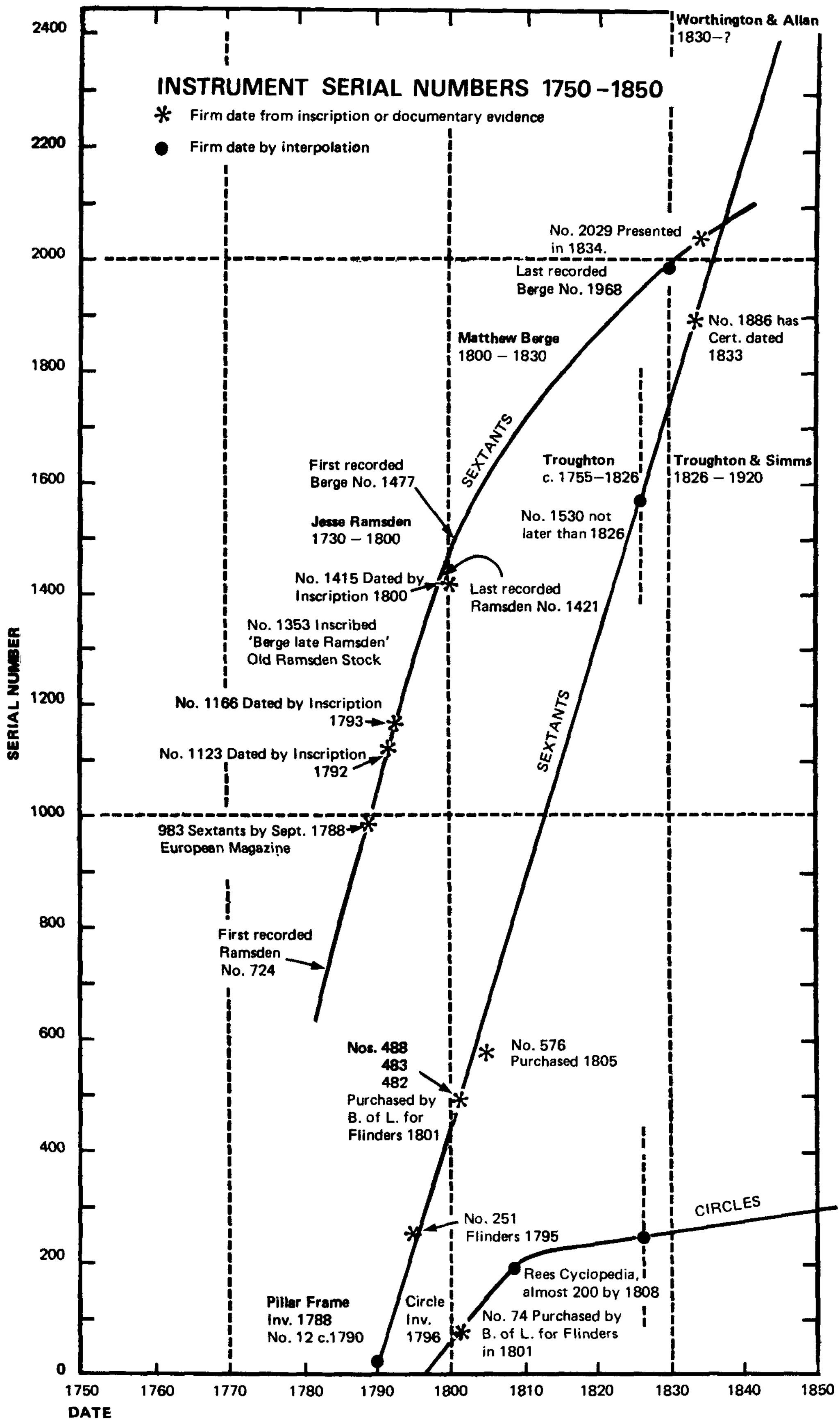


Fig. 18.4. Sextant and reflecting circle serial numbers plotted between 1750 and 1850 for the instrument makers Ramsden, Berge and Worthington, and for Troughton and Troughton and Simms.