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The World's First Sextants

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ABSTRACT

The first navigation sextant in the world was made by the London instrument maker, John Bird, in the year 1757. It, and four others by him are known to have survived, four of the five in museums in the United States, England, & Holland, and one in the possession of the author. Bird also published two booklets for the Board of Longitude on his methods of making and dividing the scales of astronomical instruments which contain brief reference to his sextants. These, taken with contemporary commentaries on his work, and newly discovered early documents, form the complete record on this major development in the history of navigation. The author has examined four of the five sextants in detail and has obtained data on the fifth. This is a comprehensive report on the historical aspects, mechanical design, and scale division of these instruments, together with the first set of photographs of all five ever published in one place.

INTRODUCTION

Invention of the Instrument of Double Reflection

The Longitude Act of 1714[1], offering the sum of £ 20,000 (approximately $2 million in today's purchasing power) for the practical solution of the problem of the determination of longitude at sea to an accuracy of 0.5 degree, may have been the single greatest factor in establishing Britain as the world's leading nation of navigators for almost a full century. The author[2] and Alan Stimson of the National Maritime Museum, Greenwich[3], have discussed the historical and technological significance of the many efforts undertaken to solve the outstanding problems, and to secure the monetary rewards. A Board, or Commissioners, of Longitude was established to evaluate submitted inventions and theories, to test results, and to provide direction and financial support in those areas which seemed most promising. Most work tended to be along the lines of the development of a Marine Chronometer capable of retaining a time reference over long periods at sea and of a Method of Lunar Distances, its theory of lunar motion, methods of computation, and sighting instrumentation capable of making the required observations.

During the earlier years of the Board of Longitude, existing instrumentation was as inadequate for the accurate measurement of a Lunar Distance (the angle between the Moon and selected reference stars as the Moon moves against the stellar background) as was lunar theory for predicting lunar motion. The cross-staff had come out of the East during the Middle Ages. The invention of the Davis quadrant (or back-staff) was over 100 years in the past. The simple quadrant and the mariner's astrolabe were even less appropriate. Thus when

John Hadley presented his new, doubly-reflecting quadrants before the Royal Society in the year 1731[4], a new order of instrumental accuracy was established. There were two variations on his basic concepts: the first, simple in construction but clumsy in use, and the second, more difficult to build but more practical, as shown in Figure 1. It was this second design which was to prove the forerunner of all 'sextant' class marine, air, and space navigation instruments.

The optical principle of both types of Hadley quadrants was the same. A rotating scanning (or index) mirror was used to reflect the line-of-sight of a

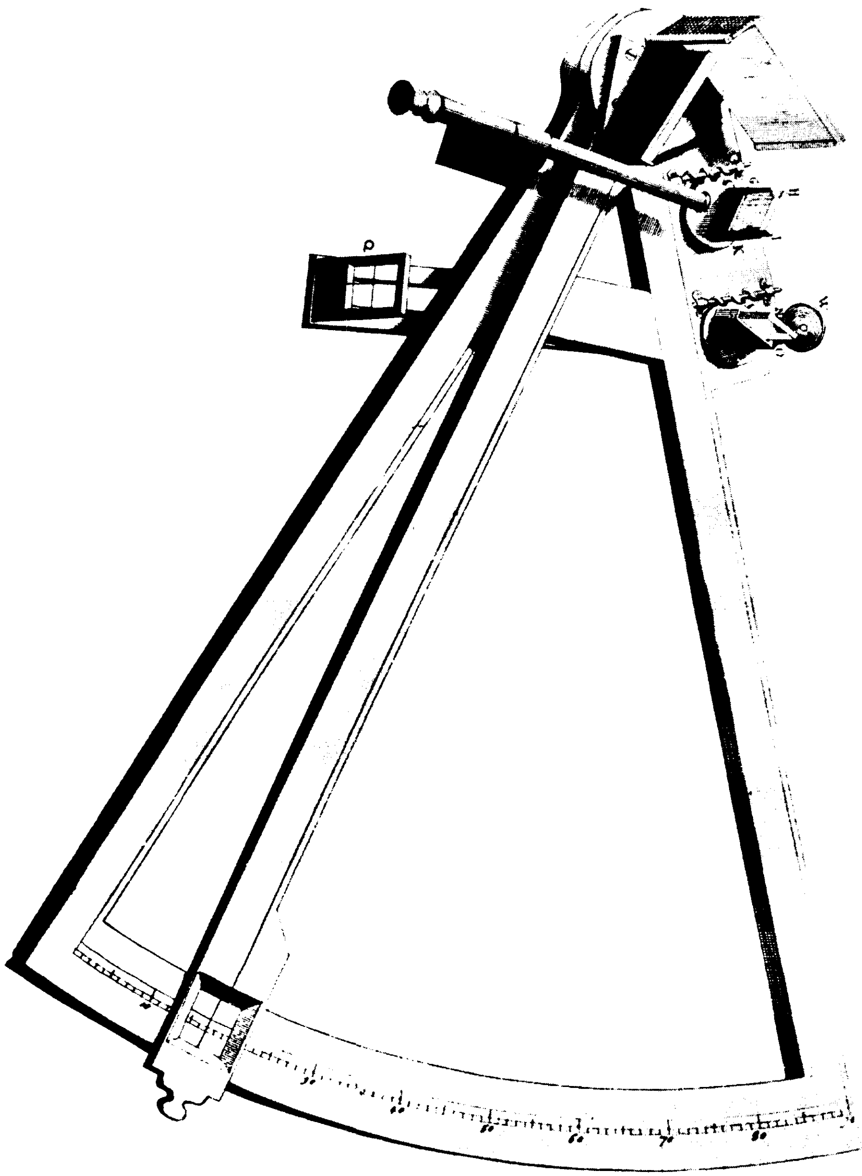

Fig. 1—John Hadley's 2nd Instrument of Double Reflection, The Generic Sextant, Fig. IV, Ref. 4.

celestial target to the half-silvered, fixed horizon glass. The observer then viewed two side-by-side (or superimposed) images, the one of the celestial target brought down to the horizon glass and the horizon itself seen through the horizon glass by means of a telescope (or peep sight in simpler versions). One degree of rotation of the index mirror (attached to the index arm) produced two degrees of optical rotation of the line-of-sight. The readout scale of 90 (optical) degrees thus had a physical length of 45 degrees. For this reason the instrument was known as a quadrant (one-fourth circle), even though it was truly an octant (one-eighth circle). Actually it seems that Isaac Newton had invented this form of instrument (somewhat similar to Hadley's first design, see Figure 2) before 1700. However, Newton was so far ahead of his times that the concept was put aside and forgotten until his original manuscript was found in the papers of Edmund Halley in 1742, shortly after Halley's death[5]. Figure 3 shows a typical instrument of the 1750 period. It had its limitations. Angle measurements were limited to 90 degrees, satisfactory for any star (or Sun) to horizon measurement but not so for a Lunar Distance which could span a large arc across the sky. It was also limited in accuracy. The readout scale was divided by diagonals to 2 arcmins, not accurate enough for a Lunar Distance (which has to be to a small fraction of a minute to be meaningful) even if the accuracy of fabrication was perfect, which almost certainly, it was not. Of course, this did not matter so much since no one was able to generate accurate tables for the future movement of the Moon.

The two-body problem in celestial mechanics is the only one that will submit to exact solution. There are no general, exact, closed-form solutions to problems of three or more celestial bodies moving in their combined interacting gravitational fields. Approximate solutions must be developed for such problems,

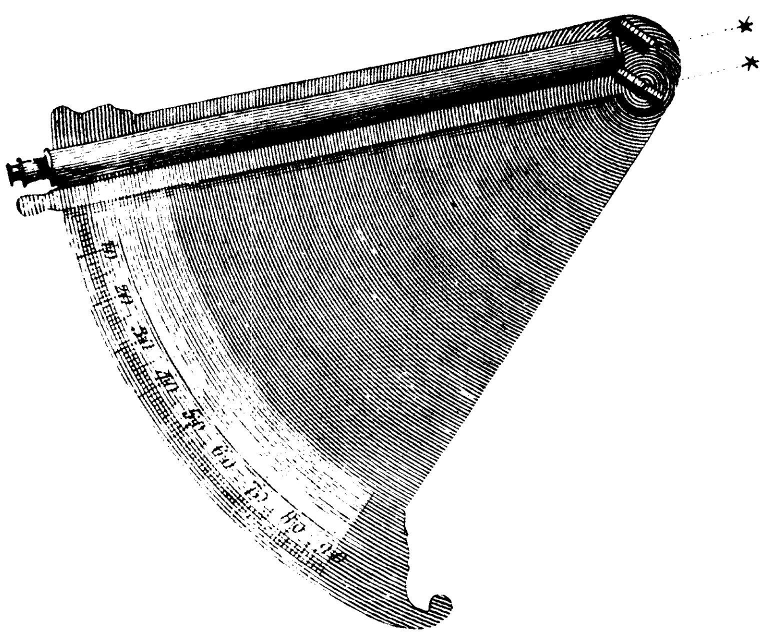

Fig. 2—Isaac Newton's Reflecting Quadrant, First Described and Illustrated in Ref. 5.

Fig. 3—A Hadley's Quadrant by the 2nd Benjamin Cole, Fleet Street, London, Circa 1750, (Author's Collection).

usually by some method of perturbations. The problem of the motion of the Moon can be treated (to a fair degree of accuracy) as a three body problem involving the Sun, the Earth, and the Moon. Tobias Mayer (1723–62), Professor of Mathematics at Göttigen, interested himself in this problem and was able to calculate a set of lunar tables in the year 1752 based upon the invention of the calculus of variations by the Swiss mathematician Leonard Euler (1707–83). These first tables of Mayer (he sent an improved set to the Board of

Longitude in 1755) were for the right ascension and declination of the Moon at 12-hour intervals, not yet a practical format for use at sea, but at least capable of experimental evaluation. Unfortunately, no instrument of sufficient accuracy was available for this operation. However, Mayer had also suggested (in 1752) the design of a 'circle of reflection' which if well made, could be used for measuring a Lunar Distance. The Confirmed Minutes of the Board of Longitude for 6 March, 1756 (reported by Alan Stimson in Ref. 6) instructed Astronomer Royal James Bradley "*. . . to cause Three Instruments to be made . . . such as he should judge most proper for the taking of Observations necessary to be made on Shipboard in the intended trials of Mr Mayer's Method of finding the Longitude of a ship at Sea. . . .*". Stimson notes that, initially, Bradley ordered only one instrument to be made, an example of Mayer's circle, and that by the London instrument maker, John Bird.

JOHN BIRD, MASTER DIVIDER

John Bird (1709–1776) was one of those initially self-taught individuals born of the English Industrial Revolution who, in turn, contributed to its advance by developing a better understanding of certain (engineering) problems than that of those who came before him, and then providing improved solutions to these problems. He was a cloth weaver by trade (as was the optical designer and perfector of the achromatic lens, John Dollond) when he moved from Durham county to London (1740) to enter the instrument maker's profession. He worked for Jonathan Sisson and, with further instruction from George Graham, was able to set up his own business by 1745. During this time, he developed his own methods of hand division of circular readout scales (described in a later section of this paper) which represented a major advance in the technology. Indeed, the accuracy of his hand work on small instruments was never equalled by any other instrument maker and only when Jesse Ramsden had devised a dividing engine for the same purpose, did the technology experience another major advance. The Dictionary of National Biography[7] provides an account of his work, which is summarized in the following. The refitting of the Royal Observatory, initiated in 1748, led to contracts to Bird for: an 8 foot radius mural quadrant, finished in 1750; a transit instrument, about 1750; a 40 inch moveable quadrant; and redivision of Graham's mural quadrant, in 1753. The quality of his work led to contracts with many English and continental observatories, including St. Petersburg, Cadiz, Paris, Tobias Mayer's in Göttingen, Radcliffe at Oxford, and Harvard University, Cambridge, New England. He was commissioned by the Board of Longitude to publish the booklets, "*The Method of dividing Astronomical Instruments,*" 1767[8], and "*The Method of constructing Mural Quadrants exemplified by a Description of the Brass Mural Quadrant in the Royal Observatory at Greenwich,*" 1768[9]. He was paid the great sum (at that time) of £ 500 for these publications and for "*taking an apprentice for seven years, and instructing him in his art and method of making Astronomical Instruments*" (preface by Nevil Maskelyne, Astronomer-Royal). He was one of the experts called on to pass upon John Harrison's chronometer (and did so favorably). Similarly, he was asked to evaluate Ramsden's dividing engine, and his positive finding served to put himself out of the business of constructing and dividing small instruments. Indeed, Sextant No. 5 of Table 1, believed to have been made for Captain Cook to use in his evaluation of Ramsden's machine divided sextants, may have been the last he ever made. The standard yards of 1758 and 1760, destroyed in the 1834 fire at the houses of parliament where they were kept as national references, were made by him. He observed the transit of Venus on June 6, 1761 at Greenwich and the annular eclipse of April 1, 1765 using reflecting telescopes of his own construction. Throughout his life he seems to have exhibited a generosity of nature (following that of his teacher, George Graham) that placed fairness above narrow personal interests. He seemed to encourage change and often was called upon by still relatively obscure individuals who were seeking a just hearing and evaluation of their ideas. There could have been no better person to be selected to make the instruments of the 'new navigation.'

CIRCLES AND SEXTANTS

Mayer's circle made by Bird for Bradley in 1756 (see Figure 4), 16 inches in diameter, was taken to sea in 1757 by Captain (later Admiral), John Campbell (1720–90). The purpose of the circle was to eliminate such errors as may result from lack of concentricity of the readout scale and the central shaft of the instrument, and inaccuracies of graduation. This was accomplished by taking a sequence of readings around the circle so as to return to one's point of departure upon the full scale (720 optical degrees). Thus by adding the values of all the readings and dividing by the number taken, an overall improvement in accuracy should result. Further, measurements of Lunar Distances of greater than 90 degrees (the limit of Hadley's quadrant) were then possible. Later tests of this hand divided circle have shown it to have a maximum scale error of 2 arcmins and regions with significantly better accuracy (see article on Circles in Ref. 11).

Campbell's observations were made between Feb. 20 and Mar. 2, 1757 while on a cruise near Cape Finisterre (9 degrees west longitude). A summary of his results are to be found in a letter dated April 14, 1760 from Bradley to the Secretary of Admiralty which was printed on pgs. CXI–CXVI of Ref. 12. The circle proved so heavy that a pole was needed to support it. Also, unfortunately, Mayer's design placed the horizon glass at an angle of 45 degrees to the axis of the telescope (as was the design practice for the Hadley quadrant). Each measurement required successive motion of the two index arms, one motion to optically zero the instrument before repeating the measurement, a feature corrected on de Borda's design about 20 years later. The afore mentioned letter discusses these problems:

> *"The observations above referred to were taken with the circular instrument constructed upon the plan proposed by Mr. Mayer, though they were not made in the manner he intended, Capt. Campbell thinking it too inconvenient to attempt to do it on ship-board; but as the principle use of this construction is to obviate the inconvenience proceeding from the inaccurate division of instruments, and as that might be sufficiently removed by the care and exactness with which Mr. Bird is known to execute those that he undertakes to make; a sextant of a radius, twice as long as that of the circular instrument, was made by him, and afterwards used by Capt. Campbell on the Royal George in different cruizes near Ushant in 1758 and 1759."*

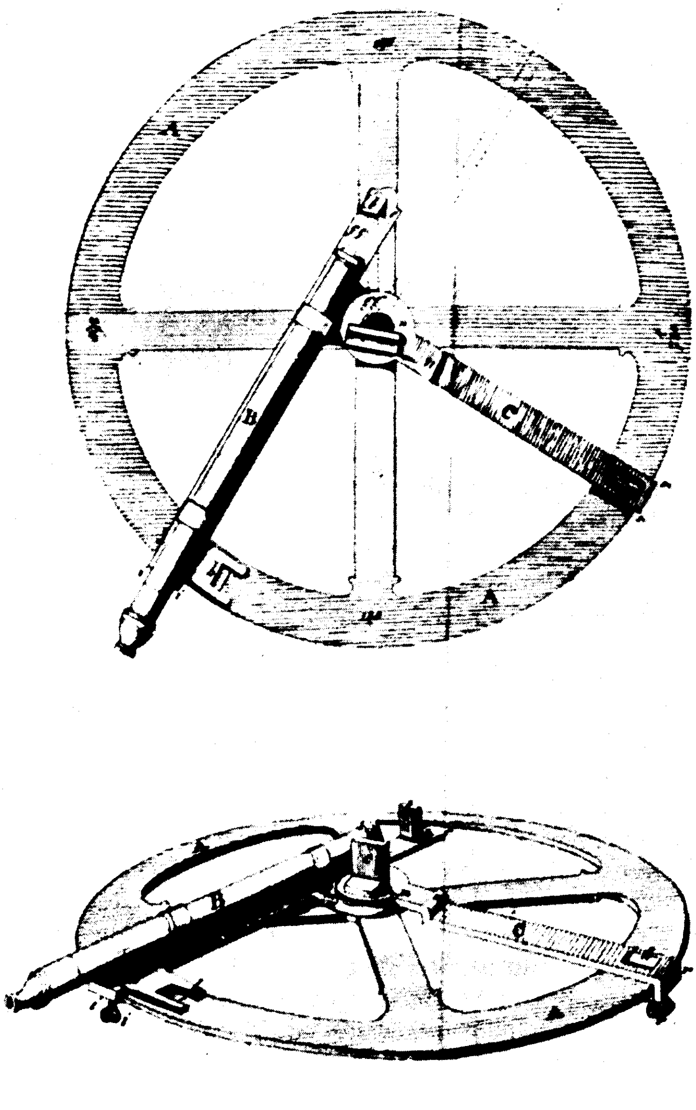

Fig. 4—Tobias Mayer's reflecting circle made by John Bird, first illustrated and described in 1767, Ref. 10.

This very sextant is shown in Figure 5. It is through the diligent search and correlation of old records that Alan Stimson (Ref. 6) was not only able to establish that this sextant, which had been at the National Maritime Museum, Greenwich, since 1963 was indeed the first, but also to determine the fate of Mayer's circle and the '3rd Instrument' Bradley was instructed to have made. Stimson writes:

> "In November 1768 the Board "*understanding that Mr. Bird has made some late Improvement which he is desirous of adding to the Sextants made by him for the service of this board 'resolved' That the Sextant which was lent to Capt. Campbell and that which Capt. Wallis had during his late voyage, be sent to Mr Bird to have those improvements made to them accordingly.*" These two statements imply that

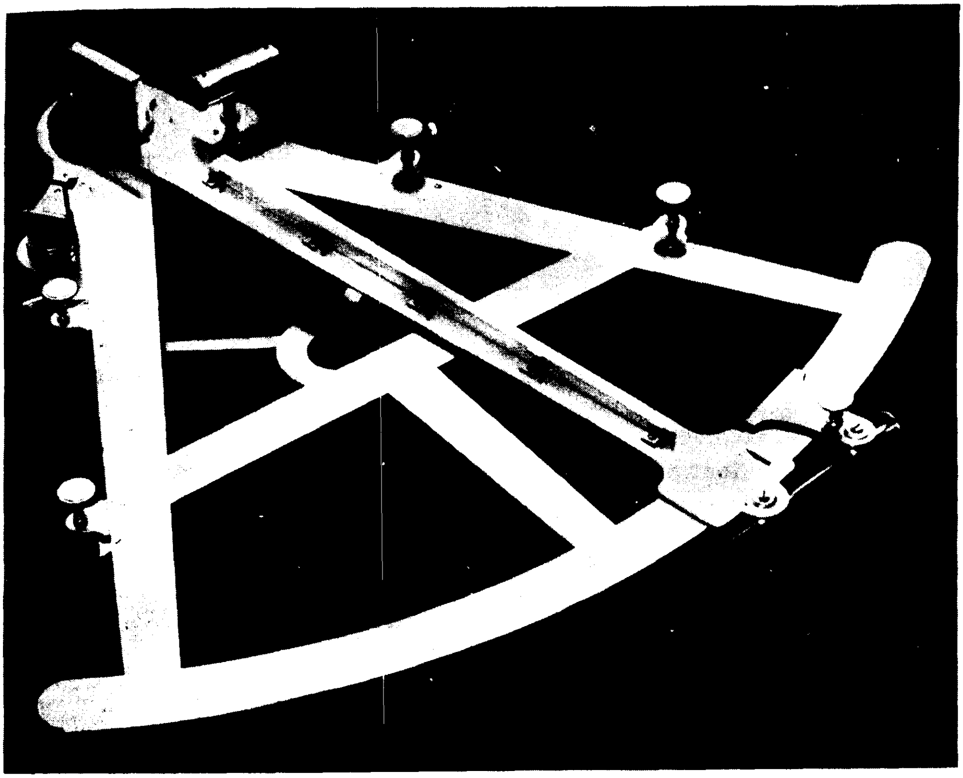

Fig. 5—The Original Sextant by Bird for Captain John Campbell, 1757, National Maritime Museum, Greenwich—Sextant No. 1.

John Bird made two sextants for the Board, Campbell's and one other, in addition to the Mayer circle, most probably the "... *Three Instruments* ..." ordered by James Bradley in 1756. This appears to be borne out by later inventory lists, for on the back of a list headed *"Instruments in the Possession of Mr. Ibbetson Nov 1st 1779"* (the Board's Secretary) is another headed *"Instruments belonging to the Board of Longitude,"* which includes Mr Kendall's three marine timekeepers and Ramsden's dividing engines. Among this distinguished company appear the following instruments:

1 Brass Circular Instrument on the plan of Hadley's Quadrant made according to the late Professor Mayer's plan, by Bird
2 Brass Hadley's Sextants of 20 inches radius, made by Bird.

Confirmatory evidence is provided by an undated inventory of the 1780s in the Royal Society records which itemizes

1 brass circular instrument by Bird—with Admiral Campbell
1 brass Hadley sextant of 20 inch radius by Bird—with Admiral Campbell
1 brass Hadley sextant of 20 inches radius by Bird lost in the fire at Greenwich"

(Note that in the above, the sextant radius given is that of the total length of the index arm, while the measured values used in this paper are the distances from the center of rotation of the index arm to the edge of the readout vernier).

Thus Wallis's sextant, the second made by Bird, was destroyed by the fire of

1779. The first sextant, however, survived, although it was lost from sight from about 1805 until it reappeared in the 1908 catalogue of the Royal United Service Museum, from where it went to Greenwich. The circle has yet to resurface, although it is possible that it was destroyed in a later fire. At the present time, exactly five sextants made by Bird are known. These are listed in Table 1, where they are presented in what is believed to be their order of fabrication, the justification for which is presented in the following sections.

MECHANICAL DESIGN

John Bird was faced with two classes of problems when he set out to design and build the first sextant. Its mechanical design had to result in an instrument of sufficient rigidity to maintain the initial alignment of its components and to provide a base upon which an accurate readout scale could be established. The second was to create the scale. The solution to the first of these sets of problems is discussed in this section while those to the problems of scale division in the next.

The five sextants of Table 1 are illustrated in Figures 5 through 11. The first three have brass frames and index arms while the last two have wooden frames with brass index arms and applied brass limbs. The telescope and tangent screw assembly of Sextant 1 are modern replacements based upon the later wooden frame instruments, yet are consistent with the size of the instrument and its place in the sequence. To begin, we can note a number of correspondences between the instruments. All five have sets of index mirror filters (shades), or a place for them, but no horizon glass filters. Further, all five have slots into which the base tang of their filter set may be inserted, or removed. This is the same system to be found on the earlier Hadley quadrants (Figure 3) where the purpose was to allow the filter set to be placed in position for either fore or back sightings. No back sightings are possible with Bird's sextants, yet he retained this feature. This is the reason there are no filters with Sextant 1. At some point in time the set was either removed, or fell out, and was subsequently lost (a common occurance with recently found Hadley quadrants). Sextant 3 has a (later ?) screw installed to prevent this from happening, as may be seen in its rear view (Figure 8). There is no handle on any of the instruments although the three largest instruments (Nos. 1, 4, and 5) have a rear bracket secured to

Table 1—Known Sextants of John Bird

1. Brass frame & reinforced index arm, 18 ¼″ radius, scale divided to ⅓ deg, vernier to 1 arcmin. Location: The National Maritime Museum, Greenwich, London.
2. Brass frame & flat index arm, 7″ radius, scale divided to ½ deg, vernier to 3 arcmins. Location: The Time Museum, Rockford, Illinois.
3. Brass frame & flat index arm, 3″ radius, scale divided to 1 deg, vernier to 6 arcmins. Location: With the author.
4. Wood (African mahogany ?) frame with brass limb and flat index arm, 13 ½″ radius, scale divided to ⅓ deg, vernier to 1 arcmin. Location: Nederlands Scheepvaart Museum, Amsterdam.
5. Wood frame (African mahogany ?) with brass limb and flat index arm, 17 ⅞″ radius, scale divided to ¼ deg, vernier to 1 arcmin. Location: The Science Museum, London.

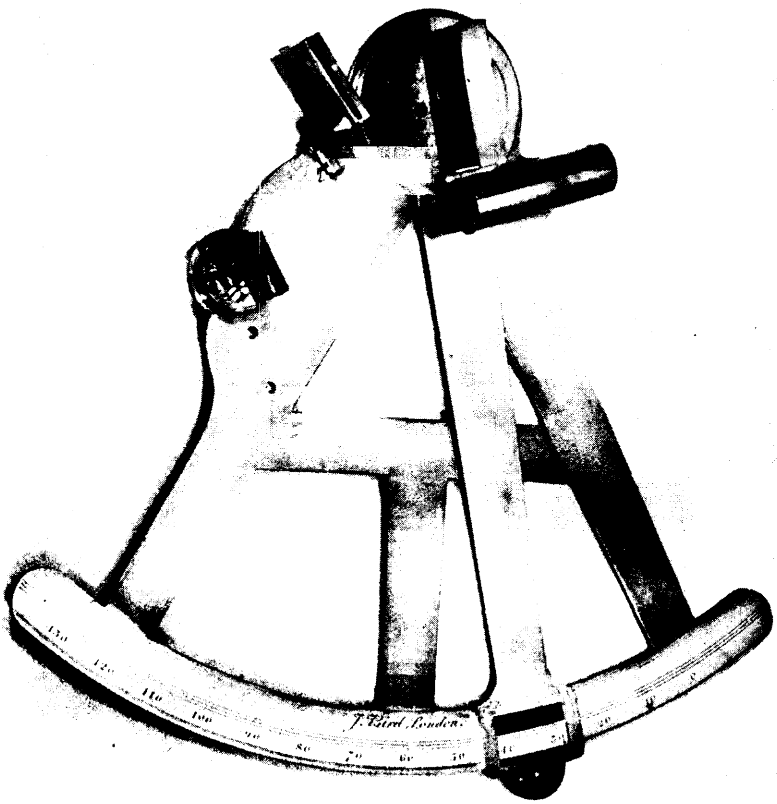

Fig. 6—The Time Museum, Rockford, IL, Bird Sextant—Sextant No. 2.

the frame by four thumb screws, with a hole for a supporting pole. Sextant 4 is shown with such a pole in Figures 9 and 10. All five sextants have only a half (lower) mounting housing for their horizon glasses, a feature which would leave them more subject to damage than they would have been with a full housing, a feature typical of both earlier and later instruments of double reflection. The three largest instruments (nos. 1, 4, & 5) have index arm tangent screw fine adjustment assemblies based on those used by Bird for his observatory instruments. (The one shown on Sextant 5 in Figure 10 has been incorrectly mounted in an attempt to duplicate the positioning employed on later instruments.) The two smaller ones (Nos. 2 & 3) just have pressure plates, since with reduced readout accuracy, there is less need for critical adjustment. The first four sextants have fixed mounted telescopes (shade tubes on Nos. 2 & 3) while No. 5 is the only one with screw-in interchangeable telescopes, a feature to become common on all later sextants.

The frames of the three brass frame sextants are of particular interest. There was no such thing as uniformly thick rolled sheet brass in the 18th century (or for much of the 19th century as well). The usual practice was to cast a flat ingot which was then hammered into sheets. This resulted in noticeable variations in thickness and multiple microfractures throughout the metal, producing

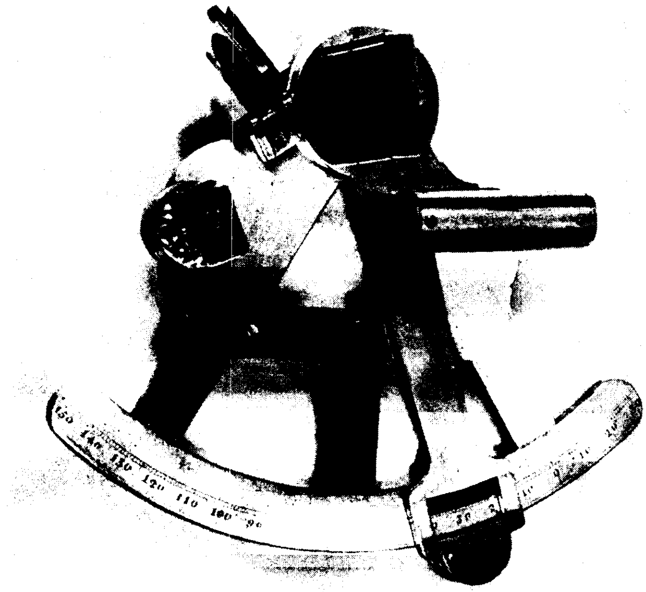

Fig. 7—Historical Technology, Inc., Marblehead MA, Bird Sextant—Sextant No. 3.

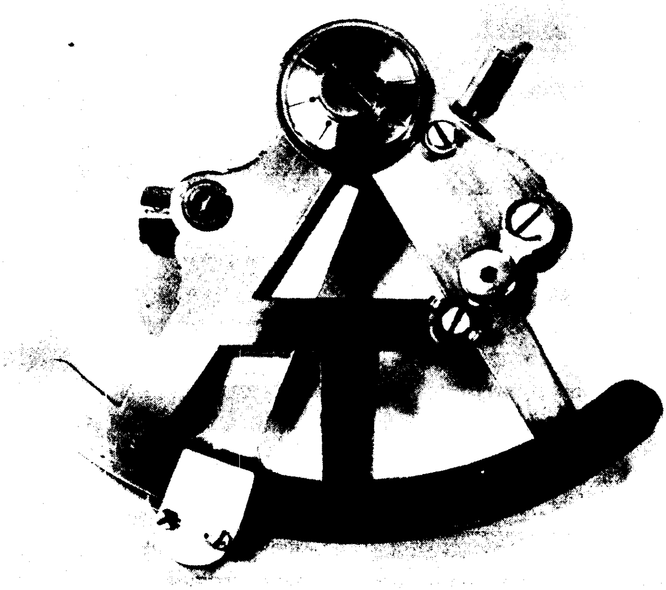

Fig. 8—Rear View of Sextant No. 3.

metal plates with serious weaknesses. The sextant frames here were not made this way. They are flat brass which vary in thickness by no more than a few thousanths of an inch. Close examination reveals circular machine marks centered upon the center of rotation of the index arm. It is more than likely that Bird worked with cast slabs of brass that he then machined in either a

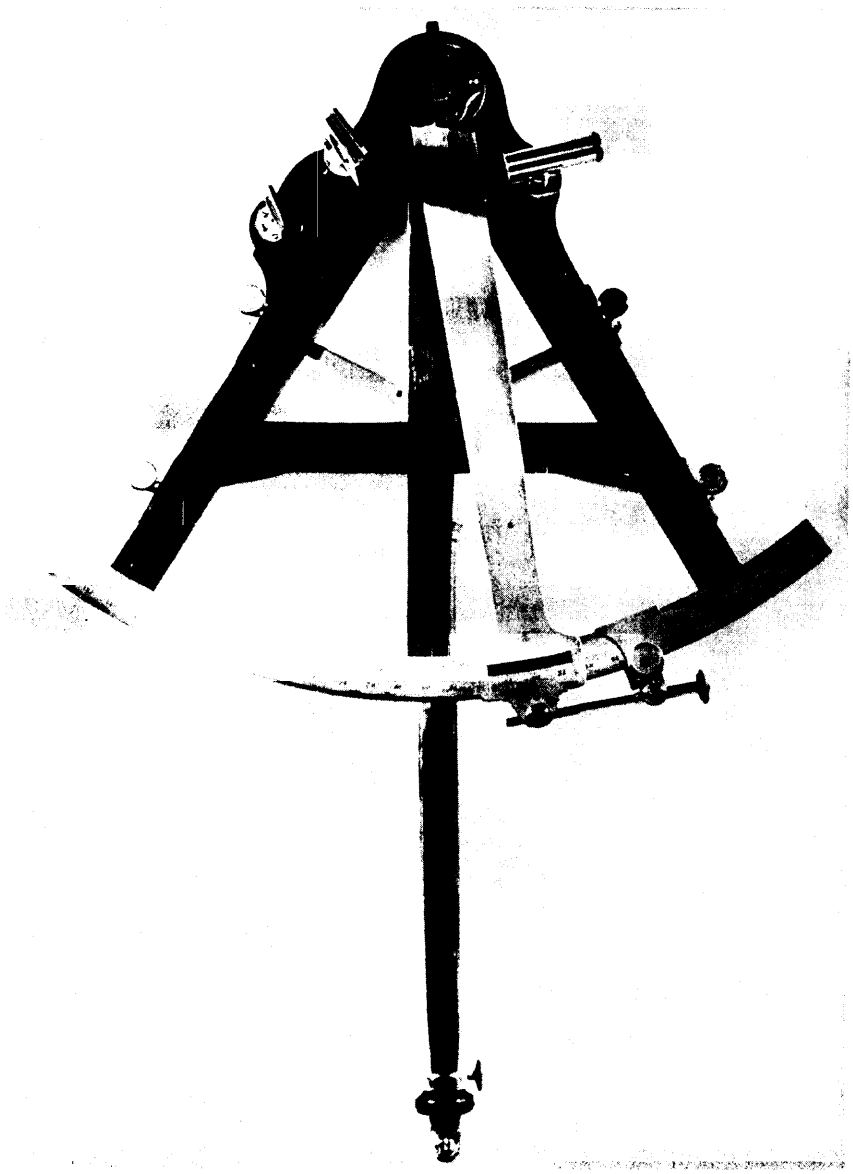

Fig. 9—The Nederlands Scheepvaart Museum, Amsterdam, Bird Sextant—Sextant No. 4.

lathe with an extremely large face plate (it would have had to be at least 40 inches in diameter for Sextant 1) or a circular shaper, the brass attached to a fixed base plate while a rotating cutter turned above it while advancing on some sort of lead screw. The author has been unable to find any record of either sort of machine, yet the results prove that one had to exist. In the following section it is shown that changes in Bird's method of scale division leads to the grouping of sextants as follows: Nos. 1 & 2, Nos. 3 & 4, and No. 5. Sextant 1 has been shown in Ref. 6 to have been the one made for Capt. Campbell in 1756. The question is how closely did No. 2 follow?

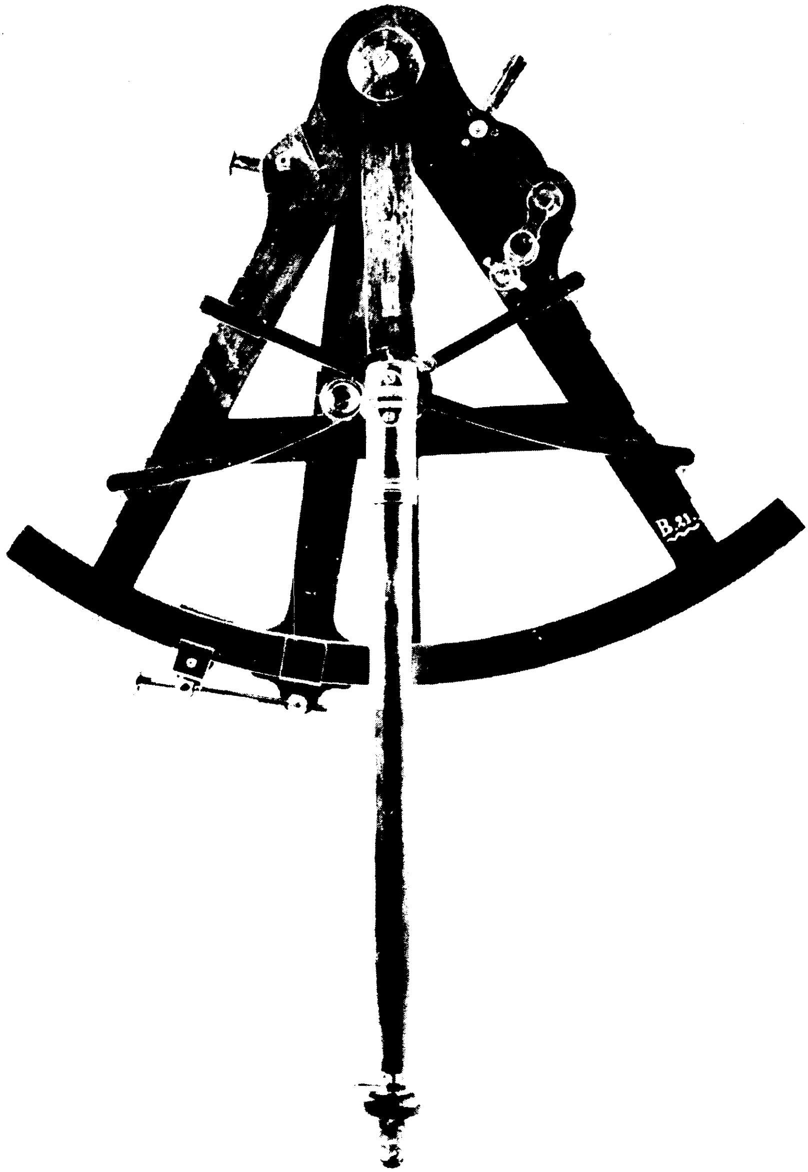

Fig. 10—Rear View of Sextant No. 4.

All five sextants have a relatively short, wide, slightly conical, index arm axis turning in a hard bronze bearing. A slit washer on the rear of all but No. 2 (see Figures 8 & 10) was used to compensate for wear. Only No. 2 has a solid washer (not illustrated). The slotted washer is a distinct design improvement and we should assume that if it is not on No. 2, then No. 2 must have been made that way and that only later were improved washers made with their sextants. Then how did No. 1 get a slotted washer? It is reasonable to assume that it was retrofitted. According to Ref. 6, the Board of Longitude Confirmed

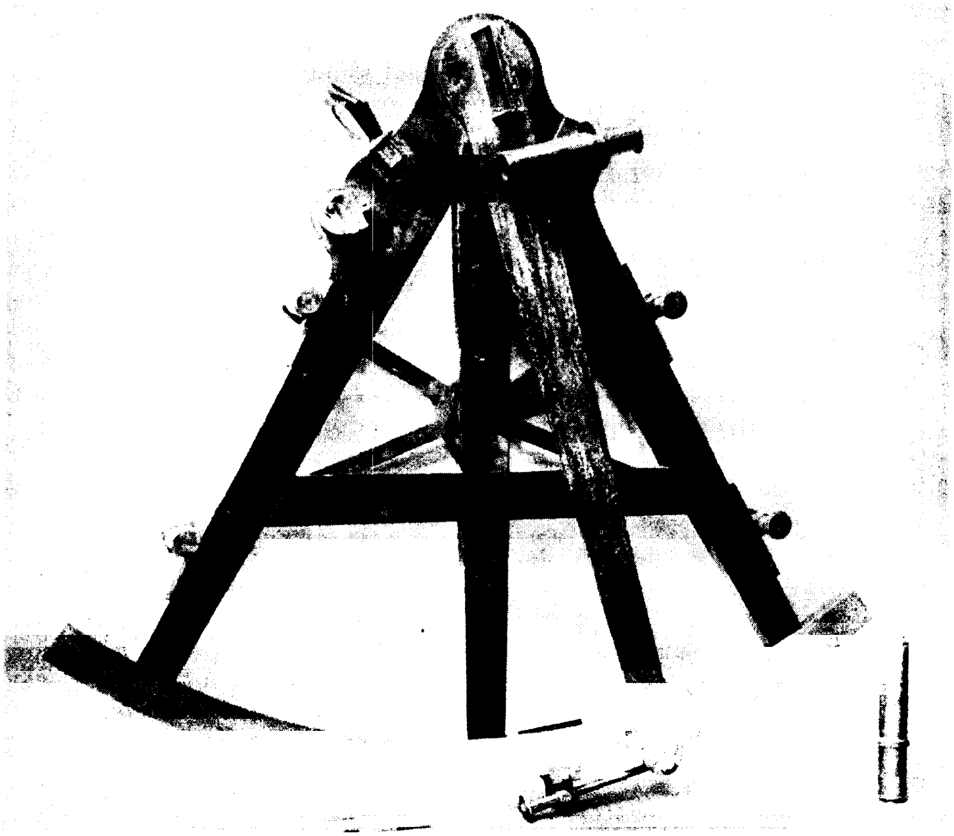

Fig. 11—The Science Museum, London, Bird Sextant—Sextant No. 5.

Minutes for Nov. 3, 1768 (previously quoted) called for the first two sextants made to be returned to Bird for him to add his latest *"improvements."* It could very well have been at this time that the slotted washer was fitted to No. 1. Since Sextant 2 does not have such a washer, it must have been made before this date, although it is not possible to tell how much before. No. 5 is believed to have been made in 1771 for Cook's voyage of 1772. Thus the dating of Nos. 3 & 4 depends upon whether they have original or retrofitted washers, and other factors as discussed in the following sections on Scale Division. No. 1 has a reinforced index arm, a feature to be found on none of the others, even No. 5 which is virtually the same size. Its method of attachment (10 small brackets) suggests that this work was done after the sextant was completed. The underside of No. 1 is also fitted with reinforcing bars (not visible). These were applied after the sextant was divided since there are screw heads right in the middle of the faint scale upon which Bird did his actual dividing, and which was then used for engraving the readout scale (also discussed in the following sections). The bars may have been applied just after construction if Bird decided then that the instrument was not sufficiently rigid for the accuracy which it was supposed to provide.

The wooden framed instruments present other problems to be considered. It is clear that they were so made because of weight considerations. Sextant 1 is too heavy to hand hold. Sextants 2 & 3 are fine but, because of their sizes, were not made to accuracies compatible with lunar observations. It is not easy to use any of the larger sextants with their supporting poles, except during periods of the calmest seas. Sextants 4 & 5 can be hand held (except for the difficulty that there are no handles). However, one must question their long term structural rigidity. Wood moves with time. There is no indication of what Bird thought about this and examination of No. 5 has not revealed any special design features which would have prevented such distortions from taking place.

SCALE DIVISION

There are several characteristics which appear common to all of Bird's hand divided scales. His actual division work was performed on a faint arc located just inside of where the engraved readout scale would be placed. This arc would be scribed with a beam compass and the same beam compass then used to mark off "60°." The 90 degree point was obtained by setting a second beam compass to bisect the 60° arc and then marking "90°." Next, points on the arc were established corresponding to some power of 2, times the size of the selected minimum scale division. For this, Bird used computed chords based upon the set arc radius and so adjusted his beam compasses. His standard of length was (according to his own account in Ref. 8) *"A [brass] scale of equal parts, by which the Radius may be measured to 0,001 of an inch, . . . each inch divided into 10, contiguous to which are nonius [vernier] divisions, viz. 10,1 inches divided into 100 equal parts, shewing 0,001 of an inch; and by the assistance of a magnifying glass, of one inch focal length, a third of 0,001 may be taken off by estimation."*

In order to divide the Royal Observatory Mural Arc of 8 feet radius, Bird called for *"five Beam Compasses, to which magnifying glasses, of not more than one inch focal length, should be applied. Let the longest beam be sufficient to draw the Arcs, and measure the Radius: The 2d to measure the Chord of 42°:40': The 3d to measure the Chord of 30°: The 4th 10°:20': The 5th 4°:40': And, if a 6th, to measure 15°, be made use of, so much the better."* Further on he also notes, *"In dividing, the points of the Beam Compass should never be brought nearer together than 2 or 3 inches, except near the ends of the arch or line to be divided; and there spring-dividers, having round points which may be put in and taken out occasionally, will best answer the purpose."*

Unfortunately he gives but little information on dividing small (sextant size) instruments, except for a short paragraph on page 12 of Ref. 8. *"Sextants, or Octants, for observing the distance of the moon from the fixed stars, should be divided by the foregoing method, great accuracy being required. If, instead of dividing Sextants to every 20' upon the limb, as is commonly done, they should be divided to 15', a Chord of 64° might be laid off, and divided by continual bissections: This would, in some measure, crowd the Limb with divisions; but it would shorten the Nonius; for 15 instead of 20 would shew one minute."* There are details presented in this booklet which, to some extent, must have been carried over to his sextant work and thus of value to this study.

Once faint chords had been struck on the faint arc, their intersections were marked by a punch. *"The prick-punch, for this purpose, must be extremely sharp, and round, the conical point to make a pretty acute angle; and as the points,* *herewith to be made, should not exceed 0,001 of an inch, when linear divisions are to be cut from them, a magnifying glass of 1/2 inch focal length should be used; by the assistance of which, the impression, or scratch, made by the points of the Beam Compass, will be very conspicuous; and if the said impression be not too faint, feeling, as well as seeing, will greatly contribute to make the points properly."* Check chords were also swung, apparently working from both the left and the right. *"If the Chord should be taken a little too long, or too short, so that the intersection be made on one side or the other of the arc to be divided, . . . the point be made in the middle between the two short lines, except at the point of 42°:40', where great care must be used in taking the Chords from the Scale."* Thus, if any such double lines, with the point between them, can be found on the faint scales of the listed sextants, there will be that much more information which may help in the determination of just how these instruments were divided.

Bird was the first to realize how important thermal expansion was in terms of accuracy of the division process and to develop methods of working within its constraints. Discussing large instruments, *"After I had found, by experience, that the expansion of the Instruments to be divided, occasioned by the increasing heat of the sun, or a contraction, by a decrease thereof, was the grand difficulty with which I had to struggle, especially when two or three hours were required to lay off the principle points; . . . and, as the heat of three or four persons in the room may produce the same effect as the sun, I never admit more than one, as an assistant: . . . and, as too much caution cannot be used, it is proper to lay off the principal points before sun-rise, or else chuse a cloudy morning."* It seems also that he restricted his division work to the Spring and the Fall so that he would not have the problems of extreme temperatures. The author has been unable to find any remarks concerning thermal precautions taken during the division of small instruments. This does not mean though, that none was needed.

Once the faint scale had been fully divided, the readout scale was engraved therefrom. Bird did not cut radial lines passing through the center and the marked points of the faint scale for, according to the article "Graduation" of Vol. XVI of Ref. 11, he was confirmed in the maxim, *"that a right line cannot be cut on brass, so as accurately to pass through two given points [the center of the arc and a division point], but that a circle may be described from any centre, to pass accurately through a given point."* Bird cut such arcs using a beam compass one point set on a line tangential to the faint arc at the division point and the other at the division point, from which he would sweep outward. On the mural quadrant, the tangential line lay upon the limb. However, the author's measurements have shown that for the sextants, the fixed point of the beam compass was off the limb. Bird could have set up a jig upon which the sextant frame was rotated one division at a time while the readout lines were scribed. In his 1767 booklet[8], Bird states that the beam compass must have *"both its points conical, and very sharp."* Ludlam states in his commentary in the 1785 reissue of Ref. 8 that the vernier was also scribed with a beam compass with a cutting-point, a triangular prism with a slope ground down to a point at one of the angles. It would be surprising if Bird did not use such a point for engraving the sextant scales, even though he stated otherwise. As it is virtually impossible to construct a precision instrument from the instructions given in

Bion's, *"Traité de la Construction et des Principaux Usages des Instrumens de Mathématiques."* The Hague, 1716, and even more so from Stone's English version, London, 1723, (popular opinion to the contrary), Bird could very well have employed techniques somewhat at variance with his printed word.

The Scales of the Earliest Sextants

The above information has prepared us for a study of the scales of the sextants of Table 1. The first two sextants are, in my opinion as derived both from mechanical design considerations and the format of their faint scales, representative of Bird's earliest work in this area, particularly since Ref. 6 proves conclusively that Sextant No. 1 (Figure 5) is the one made for Captain Campbell. It has a readout radius of 18 ¼″ with the faint scale just inside the engraved scale, as is typical of all five sextants. It is divided to ⅓ degrees (so that 64 divisions fall within an interval of 21°–20′) and read out by vernier is to 1 arcmin. As noted under "Mechanical Design," a reinforcing bar below the limb is attached by screws passing through the faint scale, and thus had to be added after division was completed. On the faint arc there are short cross lines with a point at the intersection of each for all divisions of the faint arc except at increments of 64 divisions where only dots are found, namely at readout values of 0°, 21°–20′, 42°–40′, 64°, 85°–20′, 106°–40′, and 128° (corresponding to true angular measure of 0°, 10°–40′, 21°–20′, 32°, 42°–40′, 53°–20′, and 64°). There are light scratches (quite distinct from the short dashes at the other points on the scale) marking the second, fourth, and sixth points of this list. These may have been markers which in some way were used in the process of division. Under low power binocular microscopic magnification and with illumination at just the right angle, the metal seems to have been worn away about several of these points. Could this have resulted from the erasing of the initial dashes needed to define the points? These spots were not visible when examined under both low and medium power monocular magnification and may be nothing more than wishful thinking. If it is assumed that each point was laid down with a mean accuracy of 0.001″ (Bird stated in Ref. 8 that he worked to this accuracy), then the accuracy of two points on the scale relative to each other was ¼ arcmin, ¼ of the vernier's least readout. On this basis Bird's readout precision was limited by his physical problem of spacing lines rather than by the accuracy of his division. No faint scale for vernier division has been found, although three of the remaining four sextants all have such a scale which it is supposed was used for this purpose on the lower, or outside edge of their limbs (as described in the following paragraphs). Here, the index arm rubs along the lower edge of the limb. Thus it cannot be determined if there ever was any such scale or if it has been worn off over the years.

Sextant No. 2 (see Figure 6) apparently is the second oldest of the five. Its faint arc is of 7″ radius, the divisions of which have a measured chord spacing of 0.030″ (0.03054″ by calculation). They represent half degrees of the sextant angle, which by the vernier can be read to 3 arcmins. Thus 64 divisions fit into 32 sextant degrees, or 16 degrees true angle. The readout scale marks are arcs of about 3 ½″ radius scribed about a point outside the limb of the sextant (as already noted). The readout scale extends from −5° to 135°. The faint scale extends below zero by ½ degree increments to −6°, then by 1 degree increments to $-12°$, by 2 degree increments to $-16°$, and by 4 degree increments to $-20°$. It extends above 135° by 1 degree increments to 138° and by 2 degree increments to 140°. Dots (instead of dashes) on the faint scale have been found at 0°, 32°, 64°, 96°, 120°, and 128° (corresponding to true angular measure of 0°, 16°, 32°, 48°, 60°, and 64°). Figure 12 shows part of the faint scale and readout scale for Sextant No. 2 and may (depending upon the quality of reproduction) show the faint scale dot at 64° and the cross lines at all the divisions. These points seem to represent the initial layout of the scale (0° and 120°) and the intervals corresponding to Bird's 64 bisections (32°, 64°, 96°, and 128°). Could he have here, too, made the cross lines for these points extremely faint and then rubbed them out afterwards, before starting his bisection into 64ths? There is no sign of them on this instrument even though the light guide lines for engraving his name still remain. It is probably that the divisions on the upper and lower extensions of the faint scale were used as part of the process of generating and checking the 128° point. However, I have not yet determined the actual scheme employed. If we assume that the mean accuracy of each point is the same 0.001″ as of Sextant 1, then the accuracy of two points on the scale relative to each other would be 0.7 arcmin, or (again) just under ¼ of the vernier's least readout. It may be possible for the reader to see the second faint scale in Figure 12; one marked along the outer edges of the limb in the region between 45° and 60°. Between 50° and 55° there are 10 closely spaced intervals which appear to have a close correspondence with the 10 intervals of the vernier. On either side there are additional lines at double this interval width. It will be seen that such scales have been found on two more of the sextants and that all are believed to have been used to engrave their verniers.

Scales of the Middle Period Sextants

The smallest of the known sextants is No. 3 (see Figure 7), a miniature of 3″ scale radius, divided to single degrees and reading by vernier to 6 arcmin. Thus

Fig. 12—Readout Scale of Sextant No. 2.

64 divisions fall within 64 scale degrees. The readout scale extends from −30° to 154° and the faint scale corresponds with one added marking at −32°. Clearly defined dots have been found on the faint scale only at 0° and 128°. Wear, pinpoint surface etching, and old, very light, but abrasive cleaning have made it impossible to determine if a dash or a dot exists at 64°. Figure 13, a magnified section of the scale, illustrates this problem. Although the sextant would be considered to be in extremely fine overall display condition, John Bird's faint scale has become a ghost scale with parts of it already having faded away. Only 20% of the faint arc remains and very few of the division marks are really well defined. Fortunately, the scale is clearest at the low end and I have been able to locate a double line with a between point at −27°. This is the only double line found on the four sextants (Nos. 1, 2, 3, & 5) which I have examined. It is probable that this finding provides a major clue to the actual division process, but I have not been able to unlock its secret. The vernier has ten spaces corresponding to nine scale divisions with flanking markers at +8 and −8 scale divisions. Assuming the same accuracy of 0.001″ for each scale division, a readout accuracy of 1.6 arcmins is obtained; again approximately ¼ of the vernier's least readout. No short faint scale which can be associated with vernier division has been found here.

The wooden frame, brass limb sextant at Amsterdam (No. 4) has a scale of 13 ½″ radius divided to ⅓ degrees, reading out by the vernier to 1 arcmin. The faint scale just within the readout scale has dots at 0°, 42°–40′, 85°–20′, and 128°. Thus each interval corresponds to 128 divisions, like Sextant No. 3 (maybe), and unlike sextants Nos. 1 and 2. There is also a second faint scale on the outer edge of the limb between 68°–40′ and 89°. This, again, may have been used to divide the vernier. A division point accuracy of 0.001″ for this sextant leads to a readout accuracy of about ⅓ arcmin, this time ⅓ of the vernier's least readout.

The Scale of The Last Sextant

The latest of the 5 sextants (No. 5), the large wooden frame with brass limb instrument at the Science Museum, London, which is believed to have been

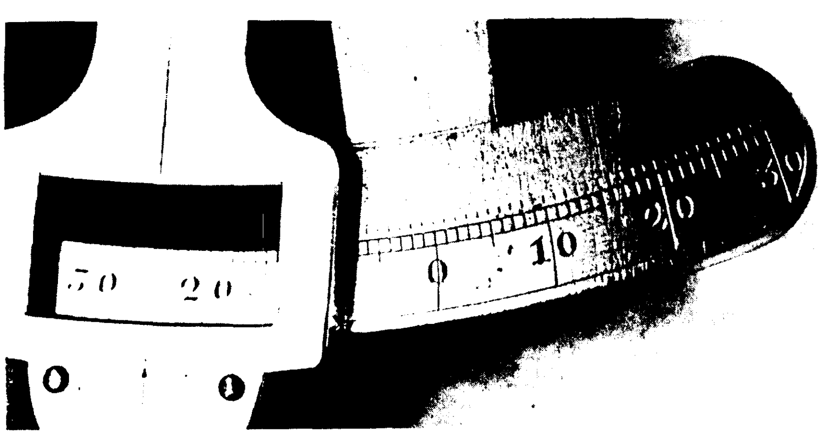

Fig. 13—Readout Scale of Sextant No. 3.

made in 1771 for Captain Cook to use on his (second) voyage of 1772, most likely is the last that Bird ever made. It has a scale of 17 7/8″ radius divided to 1/4 degrees (64 divisions in an interval of 16 scale degrees) and a vernier reading to 1 arcmin. The faint scale is clear and sharp. It corresponds to the readout scale between −9°—15′ and 135°–15′. At the low end it extends to −10°–15′ by 1/2 degree increments, with a last mark at −11°–15′, and at the high end in the same way. There are dots only at 1°–45′ (suggesting that the zero point was moved after division was completed), 65°–45′, and 129°–45′. Along the outer edge of the limb there is a second (vernier division) faint scale between 48° and 61°. Between 55° and 59° the lines are at approximately 1/4 degree intervals, and above and below this section at approximately 1/2 degree intervals. The accuracy of the scale of this sextant should be essentially the same as that of No. 1, 1/4 arcmin, if the same accuracy is assigned to its division points.

CONCLUDING REMARKS

There is still more to be determined about these sextants. I do not believe that any of them have been tested for accuracy in recent times. Not only would it be interesting to obtain data on each, it would be just as interesting to compare the brass frame instruments, as a group, with those having wooden frames, to determine if there has been a long-term structural instability in the latter. The scheme of marking the faint scale with dots and dashes changed from the early instruments (Nos. 1 & 2) and again after the middle instruments (Nos. 3 & 4). It is not known if the method of division changed as well. The method used to divide the verniers is not clear. The technique for vernier division described in Bird's 1767 booklet does not seem to apply to these small instruments. Secondary faint scales, found on three of the sextants, were (probably) used for the division of their verniers. However, how they were so used is not at all obvious, noting that when the index arm is positioned with its vernier opposite these faint divisions, they are completely covered by the lower edge of the index arm. Yet the answers to these questions may only be obtainable from the five sextants discussed here. Years of polishing and repolishing Bird's astronomical instruments at the Royal Observatory, Greenwich, have removed all signs of their faint scales. A Hadley quadrant made by Bird in 1773 as a prototype for an improvement patented by Peter Dollond was acquired quite recently by the National Maritime Museum, Greenwich. I have not had the opportunity to study this instrument and so do not know if it can help clarify some of the above. Lastly, there is the question as to whether Sextant 1 was really the first example of Bird's efforts in this direction.

Years earlier, according to Appendix XI (pg. CXXVII) of Ref. 12, Bird had made two Hadley quadrants (in brass ?) of 7″ radius. A letter from Benjamin Robins to John Bird, dated 1750, states *"YOUR two small Hadley's we observed with on board; they were much exacter than any in the ship. I have I believe forty observations made for two months together with both, where the greatest difference between them is no more than two minutes. If you could make one of the same construction, with a small short telescope (instead of the tube) which should magnify three times, by such a quadrant, of a size to be relied on to a minute,* *the longitude by Halley's tables may certainly be found to a degree.".* No one today seems to know anything about these instruments.

The results of the above study have shown several important aspects of the development of the technology of celestial navigation. Bird's mechanical design work was the beginning of a major advance in instrumentation. An accurate sextant could not have been based on the methods used to construct Hadley quadrants. He brought hand scale division to a level never before achieved. Yet it was the end of the line as well. Jesse Ramsden's circular dividing engine (as certified by Bird) was an order of magnitude more accurate than Bird's best work and much faster, and hence cheaper. Thus, in addition to their basic historical significance, the five sextants here represent a unique combination of perfected old and new technologies.

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