John Harrison and his Timekeepers

LIEUT.-COMMANDER
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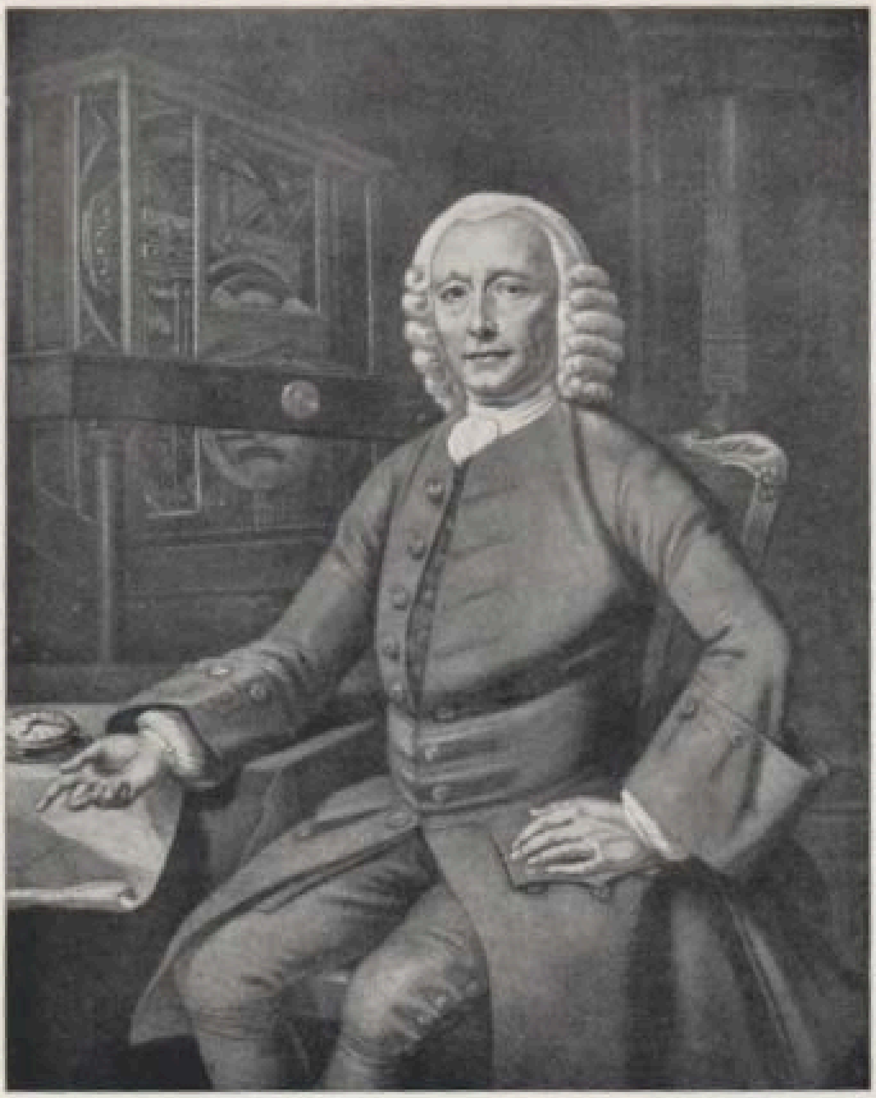
NATIONAL MARITIME MUSEUM, GREENWICH



JOHN HARRISON, 1693-1776
From the mezzotint by Tassaert, after the portrait by King, in the Science Museum

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JOHN HARRISON AND HIS TIMEKEEPERS

A LECTURE delivered by Lieutenant-Commander Rupert T. Gould, R.N., to the Society for Nautical Research at their Annual Meeting, February 21st, 1935. By courtesy of the Drapers' Company, the Meeting—over which Admiral Sir George P. W. Hope, K.C.B., K.C.M.G., presided—was held at the Drapers' Hall, Throgmorton Street.

Through the co-operation of the Admiralty, the Royal Observatory, and the Clockmakers' Company, all five of Harrison's marine timekeepers, together with the duplicate of No. 4, made by Kendall and used by Captain Cook, were exhibited, going, at the meeting.

* * *

I should like to tell you what I can about the man who first definitely solved the famous problem of finding longitude at sea.

As regards the nature of this problem, it is unnecessary for me to do more than remind you that for at least three centuries—from the beginning of the Age of Great Discoveries down to the middle of the eighteenth century—navigators were compelled to make long ocean voyages while destitute of any means of finding their longitude once they were out of sight of land. All that they could hope to do was to avoid losing it—to keep as accurate a reckoning as they could of courses steered and distances run, make such allowances as they judged best for leeway, bad steering, tide, current and so on, and trust that the final result might not, unless the voyage were unduly prolonged, be very grossly in error.

Computing longitude by dead-reckoning necessarily involved considerable and growing uncertainty as to a ship's position. It was quite usual for one which had been out of sight of land for a week to be several degrees wrong in her longitude; and this meant delay, privation, danger, and—in far too many cases—shipwreck. I could easily give you hundreds of instances in which a vessel's ignorance of her longitude led her to swift destruction; but I only propose to adduce two incidents, both of which occurred in the course of a single famous voyage.

In April, 1741, Anson's *Centurion*, having passed through Le Maire strait, was fighting her way round the Horn. In such circumstances the golden rule, of course is to make westing. So Anson stood south-westward until, by his reckoning, he was fully 10° to westward of the western coast of the Cape. He then turned northward; and soon after re-crossing lat. 55°S. he sighted land *right ahead*. It was Noir Island, off the south-west entrance of Magellan strait. An unsuspecting easterly current had robbed him of every scrap of his estimated westing, and he was compelled to stand south-westward once more and spend many days in making a sufficient offing.

In the circumstances this delay was much more than inconvenient—it involved serious loss of life. As invariably happened in long voyages—until Cook showed how it could be avoided—scurvy had broken out on board the *Centurion*; and Anson with his men dying like flies, stood northward—as soon as he dared—for Juan Fernandez, where he hoped to land his sick and obtain fresh vegetables. In the ordinary way, he would have steered to get into the latitude of that island (about 35°S.), a long way to the eastward or westward of it, and then have run it down along its parallel. But in view of the paramount urgency of saving time (a month of the present death-rate would have left him too short-handed to put the ship about) he sailed straight northward for the island—with the result that he reached its latitude without sighting it, and remained entirely uncertain whether it lay to eastward or to westward.

At first he imagined that he was to the eastward of the island—as, in fact, he was—and he accordingly beat westward until, unknown to him, he was within a few hours' sail of it. Then he reversed his opinion—and his course. A two days' run eastward gave him, for the first time, some definite information as to his position—for he then sighted the coast of Chile, and once more set himself to beat westward along 35°S. Ultimately, he anchored off Juan Fernandez on June 9th, 1741—having been within easy distance of it on May 28th. The double uncertainty, as to his own longitude, and as to that of the island (a necessary consequence of discoverers' inability to fix the longitudes of their discoveries), had cost the lives of some seventy or eighty men, who would probably have recovered if they could have been got ashore. Such was the experience, in comparatively recent times, of a well-found King's ship with a very careful navigator.

Before this, however, something had been done towards putting an end to a state of matters deplored alike by seamen and by merchants. In 1714 a petition from the London shipping interests induced the Government to appoint a Committee to consider the whole question of finding longitude at sea. It heard a considerable amount of evidence on the subject—much of the most important being a written statement by Sir Isaac Newton, which enumerated various methods of obtaining longitude, " . . . . true in the Theory, but difficult to execute." It is noteworthy that he puts the following method first:

> One is, by a Watch to keep time exactly: But, by reason of the Motion of a Ship, the Variation of Heat and Cold, Wet and Dry, and the Difference of Gravity in different Latitudes, such a Watch hath not yet been made.

Such a "Watch" would, of course, afford a simple and complete solution of the problem. A ship's longitude is the difference between the meridian she happens to be on and some standard meridian—say, Greenwich. She can obtain her local time—the time of her meridian —by comparatively simple observations; if she also knows Greenwich time, the difference gives her longitude. But in Newton's time, as he remarks, no known timekeeper was capable of going, at sea, with anything approaching the requisite accuracy—and, judging by the formidable catalogue of difficulties which he enumerates, it is not hard to infer that he regarded the construction of such a timekeeper as but little removed from impossibility.

Newton also discussed various methods of obtaining a standard of time, for comparison with the ship's local time, by astronomical observations—by eclipses, occultations, the movement of Jupiter's satellites, and the motion of the Moon in the heavens (as noted by observing her distance from the Sun or from conspicuous stars). Of these methods, all except the last-named resemble the celebrated American horse which had only two defects —one being that, if loose in a field, it was exceedingly hard to catch; the other that, when caught, it was of no use for any purpose. Attempts have often been made to steady an astronomical telescope (and, usually, a platform carrying the observer as well) at sea by means of gimbals, gyroscopes, etc.—a scheme of this kind is to be found in Besson's *Le' Cosmolabe* (Paris, 1567), and there have been many since—but the mechanical difficulties alone, are most formidable; and the time resulting from such observations varies with the state of the atmosphere and the instrumental power employed.

The last method—that of "lunar distances"—is sound in theory, and was actually in considerable use from about 1770 to 1907 (when the *Nautical Almanac* ceased to publish computed distances). If the Moon's motion be known with sufficient accuracy, tables can be drawn up forcasting her angular distance, as observed on some standard meridian (*e.g.* Greenwich), from the Sun or suitable fixed stars. These distances can also be observed (by means of the sextant) on board ship; and, by interpolation, the Greenwich time corresponding with such distances can be taken out of the tables.

But in Newton's day, and long afterwards, this method was impracticable. The "lunar theory" was too defective for the Moon's position to be forecast with sufficient accuracy—and the sextant was unknown. Actually, Newton did much to remove *both* objections. As everybody knows, he laid the foundations of all modern mathematical astronomy in the *Principia*, and thus pointed the way to a complete theory of the Moon's motion; also (which is not so well known) he devised an instrument, for use at sea, embodying that principle of double-reflection which is the essence of the sextant—although, *more suo*, he left this to be re-discovered by Hadley (and, simultaneously, by Godfrey of Philadelphia) in 1730, after his death.

It was Nevil Maskelyne—of whom I shall have more to say later—who brought the lunar method into practical use. He published an account of its principles in his *British Mariner's Guide* (1763) and instituted, four years later, the *Nautical Almanac*—in which he gave, for the first time in the history of navigation, lunar distances from the sun, and seven selected stars, computed for every three hours at Greenwich. You will remember that Cook in his first voyage round the world (1768-71) had no timekeeper, but was able on many occasions, to find his longitude within 1° (and often much nearer) by means of lunars. On the other hand, in his second voyage he carried a timekeeper; and before long one finds him putting his main trust in this, and only using his lunars as a check on its rate—and that, I think, fairly epitomises the respective merits of the two methods.

To return to the 1714 Committee. On their recommendation the Government, in 1714, passed an Act (12 Ann. cap 15[1]) offering a graduated scale of rewards for any "generally practicable and useful" method of finding longitude at sea. The criterion of the method was to be the amount of its error in determining a ship's longitude at the end of a six weeks' voyage. If this error did not exceed sixty geographical miles, the inventor's reward would be £10,000. If the error were less than forty miles, the reward payable was £15,000. And if the method were proved accurate to within 30 miles, £20,000 would be paid. Other nations, it should be noted, had offered rewards of this nature in the past; but this sum of £20,000 was by far the largest—and has the additional distinction of being the only reward of the kind which was ever paid.

The Act also established a permanent body of Commissioners, charged with supervising

[1] By modern numeration, 13 Ann. cap. 14

all competition for the rewards, and empowered to advance small sums in furtherance of methods which appeared promising. They were known as the Board of Longitude (1714-1828) and comprised, *ex officio*, a considerable number of dignitaries, about one-third of whom might be presumed to have some rudimentary knowledge of navigation. It is almost unnecessary to say that they at once became the immediate and accessible target of every crank, swindler, fanatic, enthusiast and lunatic in or out of Bedlam. Here are one or two passages from their minutes (preserved at the Royal Observatory, Greenwich):

(Jan. 25th, 1772) A person who calls himself John Baptist desiring to speak with the Board, he was called in and showed them some schemes and drawings of figures which he desired they would enable him to publish; He was informed it was not in their power . . . . He was then desired to withdraw.

(June 13th, 1772) A Memorial from Mr. Owen Straton was read, proposing a method of finding out the Longitude by means of an Instrument of his invention, and the said Mr. Straton, who was attending, being called in, and it appearing that the instrument proposed is a Sun Dial, he was told it could not be of any service, and then withdrew.

(June 11th, 1796) A letter was read from Dr. Woeman, a native of Saxony, acquainting the Board that he can express π and the ratio of 1 to $\sqrt{2}$ in integrals, and that this comprehends the discovery of the Longitude. He was informed that the Board do not receive proposals of this nature.

(August 3rd, 1812) M. Metiriet was informed that the Board declined any interference with the quadrature of the circle.

After remaining on offer to the world for some fifty years, the £20,000 reward was won, in defiance of Newton's opinion, by an accurate marine timekeeper. The extraordinary nature of this achievement can best be appraised after devoting a few minutes to the history of earlier efforts at constructing such a machine.

The mainspring, whose invention rendered portable clocks and watches possible, is known to have been used by Peter Henlein of Nuremberg, soon after the year 1500. Not very long afterwards—in 1530—the use of such portable timekeepers to find longitude was recommended by Rainer van den Steen (*Lat.* Gemma Frisius), a Flemish astronomer and mathematician, in his *De Principiis Astronomiæ et Cosmographiæ*. But their habitual errors of half an hour, or so, *per diem*, put them hopelessly out of court for purposes of navigation. Van den Steen seems to have had some inkling of this, for he recommends the mariner to check their rate of going frequently by comparing it with that of a sand-glass or water-clock; although, if these were better timekeepers, it would seem advantageous to embark them, and to leave the spring-clock behind.

The first man who is definitely known to have made a marine timekeeper specifically designed to find longitude at sea was the famous Christian Huygens, of Zulichem in Holland—a man who would undoubtedly have been regarded as the greatest and most versatile scientist of the seventeenth century if it had not been his misfortune to be contemporary with both Leibnitz and Newton. Huygens (1629-95) was the discoverer of Saturn's ring and its largest satellite; he propounded the undulatory theory of light; he was one of the first men to suggest the use of a pendulum in a clock; and he was certainly the first to give the correct geometrical theory of the pendulum's motion.

In 1660 and succeeding years he designed, and had made, several marine timekeepers.

These were mounted in gimbals, and controlled by small pendulums swinging half-seconds. They were spring-driven, but some embodied a "remontoire"—a device of which we shall hear more later, and which, in effect, provides a more or less constant supply of power to impel the pendulum or balance of a clock or other timekeeper; this supply being periodically renewed, at short intervals, from the main source of power. Unfortunately a pendulum will only measure time accurately when it swings from a fixed and perfectly motionless support—a condition of things quite impossible to secure at sea. And as, in addition, Huygens' pendulums were not compensated for temperature, it is not in the least surprising that his marine clock, while deserving much praise as a plucky effort—the first of its kind ever made—none the less proved, on trial, of no real utility at sea. No specimen of these machines has, so far as is known, been preserved—but a very fine replica of one has recently been made in Holland, conforming as exactly as possible with Huygens' own description and drawings. It is on exhibition, going, in the Scheepvart Museum, Amsterdam.

Another pioneer whose work deserves mention is Jeremy Thacker, of Beverley in Yorkshire. His machine, whose description he published in 1714, was spring-driven, suspended in gimbals, and kept going *in vacuo*—a glass dome, exhausted of air, covering the whole of the mechanism. This is, I believe, the earliest appearance of a plan now followed in the most accurate observatory clocks. To avoid disturbing the vacuum—which, however, was probably not high—Thacker wound his machine through a stuffing-box, and provided it with an auxiliary spring to keep it going while being wound. Also, he is the first man to use the word "chronometer" to denote a marine timekeeper—or, for that matter, a time-measuring instrument of any kind. The weak point of his machine is that it contains no provision for the effects of heat and cold—which, however, mitigated by the vacuum, would still affect its rate of going. He suggests calibrating it—ascertaining its rate in various temperatures, and then keeping a record of those, to which it was exposed—a laborious and inaccurate plan. He states that he made one, and that its rate on shore, by star transits, never exceeded 5 or 6 seconds per day: but I am afraid the rigorous tests at sea would have told rather a different story.

A little later, the problem attracted the attention of Henry Sully, an English clockmaker who spent most of his life in France. The horological collection in the Conservatoire des Arts et Métiers, Paris, contains a piece which, although unsigned, I am inclined to regard as one of his early efforts. It is a spring-driven clock with a verge escapement, but no balance-spring, and is not compensated for temperature. It is probably the oldest, and worst, marine timekeeper which still exists.

In 1724 Sully produced a marine clock of great originality. It was spring-driven (a later model had a remontoire, re-wound four times an hour) and controlled by a balance connected, by means of a fine wire plying between two cycloidal cheeks, with a weighted lever pivoted on anti-friction wheels. As the balance oscillated, the lever rose and fell—acting, to some extent, as a horizontal pendulum. Trials of the machines on land, and in smooth water, promised well; but a test carried out in 1726 on the open sea gave such disappointing results that Sully abandoned this design in despair. It must be added that, lacking any form of compensation for temperature, it could never have been a really accurate timekeeper, even on land. Although much disheartened by his ill-success, Sully set to work manfully on a new form of machine timekeeper; but he died at forty-eight (October, 1728) before he had made much progress with it. There is a specimen of his 1724 machine in the Clockmakers' Company Museum, Guildhall.

In 1728, also, Jean-Baptiste Dutertre, an eminent French clockmaker, constructed a small maritime clock which is still to be seen in the Conservatoire des Arts et Métiers. It has a spring movement suspended in gimbals, and is controlled by two pendulums geared together, and swinging [illegible] seconds in opposite directions—the purpose of their connection being to nullify the effect which the ship's motion would have upon the period of either separately. Actually, the friction of the gearing would entirely destroy their time-measuring properties—which, in any event, could not have been great, since they were not compensated for temperature. This machine of Dutertre's represents the best which the clockmakers of the early eighteenth century—the very men who, by their technical training and practical knowledge, were in honour bound to attack the problems involved in constructing an accurate marine timekeeper—could contribute towards a solution of the problem of finding longitude at sea; and, frankly, it was a very poor best. None of them seems to have had so much as an inkling of the fundamental difficulties involved.

In the same year (1728) in which Dutertre produced his museum piece, there came to London a young Yorkshireman—John Harrison of Barrow-on-Humber. Born in 1693, the son of a carpenter, he had been brought up to follow his father's trade, but he had managed to educate himself sufficiently to be able to make a little money by land-surveying; and also, without ever serving a day's apprenticeship to any clockmaker, to acquire sufficient horological knowledge to repair, and even construct, clocks. Several of his early efforts in this direction, with wheels and pinions of wood, are still extant—one, now in the Science Museum, having been made as early as 1714, when he was only twenty-one.

He brought with him specimens of two original inventions which he had successfully applied to his clocks—a form of pendulum (known, from its appearance, as the "gridiron") composed of brass and steel rods, so arranged that its period was practically unaffected by changes of temperature; and a complicated but highly efficient escapement (known, for a similar reason, as the "grasshopper") which never required oiling and gave a practically continuous impulse with a minimum of friction. And he also brought drawings of a marine timekeeper which he proposed to construct—such was his provincial optimism—with the (financial) help of the Board of Longitude.

Before interviewing the Board, however, he called at the Royal Observatory and was received by Halley, then Astronomer-Royal, with the courtesy, which it is a tradition of the office (*crede experto*) to extend to inquisitive strangers. Halley told him plainly that the Board would not advance him a penny, and suggested that he would do better to lay his plans before George Graham, F.R.S., the leading London clockmaker—generally known, in the trade, as "Honest George Graham". To Graham, Harrison accordingly went, and in him he found a kindred spirit (Graham was also a North-countryman, born in Kirklinton, Cumberland). Like Halley, Graham advised him to make his machine before applying to the Board for assistance—but he solved the crucial problem of funds by advancing Harrison the requisite sum without security or interest. I believe, but am not sure, that the amount was £200. This most generous act set Harrison upon a path which led him, ultimately, to fame and fortune—although, long before he grasped them, his benefactor was resting, beside his own master Tompion, in Westminster Abbey.

Harrison returned to Barrow, and spent the next six years (1729-1735) in building his first marine timekeeper—which is now going in front of me.

It is really a large marine clock, controlled by two huge straight-bar balances mounted on portions of large anti-friction wheels, and connected by cross-wires running over brass arcs. They swing, in consequence, as if geared together (but with far less friction) and a ship's motion has no appreciable effect on their period of oscillation. They are controlled by four helical balance-springs, in tension; and a triple "gridiron" of brass and steel rods automatically varies the tension of these springs so as to counteract the effect of heat or cold on the springs themselves. This is the first compensation for temperature ever applied to any time-keeping instrument controlled by a balance.

The wheels (except the escape wheel, which is brass) are of *wood* (oak) with the teeth, also of oak, morticed into the rims. They are all mounted on anti-friction wheels, and move with remarkable freedom. There is no remontoire. Two main-springs drive a single central fusee, provided with a "maintaining spring" to keep the machine going while being wound (which was, originally, accomplished by pulling a cord wound on the fusee itself). There are two escapements, of the "grasshopper" pattern, one being mounted on each balance-staff. The machine goes for about 38 hours at one winding, and shows seconds, minutes, hours and days. For use at sea, it was enclosed in a wooden case, suspended by springs from a gimbal-frame.

You will be relieved to hear that I do not propose to describe Harrison's later timekeepers in so much detail. I have dwelt upon this, because it is the first—not only the first which Harrison constructed, but the first accurate marine timekeeper which was ever made at all, anywhere in the world. Crude it may be, but one cannot call it primitive—in essentials, it provides a complete solution of one of the most intricate and difficult mechanical problems which Man has ever been called upon to solve. Reflect, too, that Harrison not only made it—which, considering his circumstances and lack of horological training, would have been wonderful enough—but also invented and designed it.

Having tested No. 1 successfully on board a barge in the Humber, Harrison brought it to London in the spring of 1736. On the Royal Society's recommendation, the Admiralty allowed it to be embarked, with its maker, on board H.M.S. *Centurion* for a voyage to Lisbon. The correspondence on the subject between Sir Charles Wager, then First Lord, and Captain George Procter of the *Centurion*, is worth quoting:

(Wager to Procter) Admiralty, May 14th, 1736

The Instrument which is put on Board your Ship, has been approved by all the Mathematicians in Town that have seen it (and few have not) to be the Best that has been made for measuring Time: how it will succeed at Sea, you will partly be a Judge . . . . The Man is said by those who know him best to be a very ingenious and sober Man, and capable of finding out something more than he has already, if he can find Encouragement. I desire, therefore, that you will see the Man be used civilly, and that you will be as kind to him as you can.

(Procter to Wager) *Centurion*, at Spithead, May 17th, 1736

I am very much honoured with yours of the 14th, in Relation to the Instrument I carried out and its Maker: the Instrument is placed in my Cabin, for giving the Man all the Advantage that is possible for making his Observations, and I find him to be a very sober, a very industrious, and withal a very modest Man, so that my good Wishes can't but attend him; but the Difficulty of measuring Time truly, where so many unequal Shocks and Motions, stand in Opposition to it, gives me concern for the honest Man, and makes me feel he has attempted Impossibilities: but, Sir, I will do him all the Good, and give him all the Help, that is in my Power, and acquaint him with your Concern for his success, and your Care that he shall be well treated . . . .

I like Captain Procter's letter—and you should note that it is the letter of a sick man; he died soon after reaching Lisbon. In consequence, no official report of how No. 1 performed on the outward voyage is extant—but, if we are to judge from the sequel, it must have kept good time. Harrison came home in the *Orford*, and here is an official certificate given to him by Roger Wills, her Master.

When we made the land, the said land, according to my reckoning (and others) ought to have been the Start; but, before we knew what land it was, John Harrison declared to me and the rest of the ship's company that, according to his observations with his machine, it ought to be the Lizard—the which, indeed, it was found to be, his observation showing the ship to be more west than my reckoning, above one degree and twenty-six miles.

It is noteworthy that the general direction of the comparatively short voyage from Lisbon to the mouth of the Channel is closely aligned to the meridian, and that in consequence errors of dead reckoning would have their minimum effect upon a ship's estimated longitude —yet, even then, a discrepancy of nearly a degree and a half appears after she has spent a few days out of sight of land. Particulars of No. 1's own error at the time of this landfall have not been recorded, but it must have been quite trifling—a few seconds, at most.

In consequence of Wills's certificate, the Board of Longitude began to advance small sums to Harrison from time to time, which enabled him to construct improved versions of No. 1. The latter was not tried again at sea, but it continued going in Harrison's house (he had now settled in London) for thirty years continuously—from 1736 to 1766. When I say *continuously*, I mean exactly that—it was never stopped for cleaning. To most people with even a smattering of mechanics this may sound incredible—but it is true. Unlike all other clocks and watches, Harrison's three large marine timekeepers—Nos. 1, 2 and 3—require no oil at all. At practically every point where friction occurs, the surfaces in contact are self-lubricating; one being of lignum-vitae (a naturally greasy wood) and the other of polished brass. Harrison discovered that such bearings, so long as their load is not excessive, run themselves in and work perfectly un-oiled. In consequence the three big timekeepers never require to be stopped, cleaned and re-oiled; and it adds to the pathos of the *Centurion's* struggle round the Horn, and her long search for Juan Fernandez, to reflect that the machine which she had once carried, and which could have saved many of her men, was then marking time in London.

In 1737-1739 Harrison built a second timekeeper—which I also have here. No. 2 follows No. 1 in its outline and general mechanism, but is more compact and much more strongly built. As a consequence, it is considerably heavier—102 lb. as against 72 lb. The bar-balances, which weigh 6½ lb. each, are almost hidden from view behind the massive brass plates of the movement, and the train wheels are now all of brass—although the pinion-teeth, as in No. 1, are still formed of little lignum-vitae rollers turning on fixed brass pins. There is a remontoire, rewound every 3¾ minutes—16 times an hour. The gridiron compensation is considerably simplified, and rendered adjustable. Although an excellent timekeeper—I believe it to have been capable of winning at least the £10,000 reward—No. 2 was never tried at sea. I imagine that the Board of Longitude were opposed to such a proceeding, on the ground that we were then at war with Spain, and that the machine might fall into enemy hands.

Now begins the most obscure period of Harrison's life. We have seen that it took him six years to make his first machine, and only two to complete his second. But the construction of his third timekeeper occupied no less than *seventeen years* (1740-1757).

It is by far the most complicated of all his machines (it contains, as I have reason to know, 753 separate parts) and the most difficult to understand. There can be no doubt that Harrison intended it to be his masterpiece, and that he lavished on it every mechanical refinement which, in his judgment, could possibly tend to improve its performance; equally, he spent years of incessant experiment with the machine itself, when partially completed, to determine the most suitable proportions of its principal working parts. It is known to have repeatedly undergone fundamental alterations: some traces of which—such as holes cut to accommodate an additional (and discarded) mainspring-barrel—are still visible.

In its main outlines, it departs radically from its two predecessors. The bar-balances are replaced by two large balance-wheels (connected by cross-wires as before) and their arc of oscillation considerably increased—this affording additional security against their motion being disturbed by that of the ship. They are controlled by a single spiral balance-spring, whose effective length is varied (and the effect of alterations in temperature thereby compensated) by a simple bi-metallic "compensation curb"—a compound strip of brass and steel which is the ancestor of all the similar strips now used in the balances of chronometers and high-class watches. There is a remontoire, let off every 30 seconds. It is the only *mechanically-perfect* remontoire I have ever met with—and I have studied more than a hundred devices of the kind. It gives an *absolutely constant* torque at the escape-wheel, whether its driving springs are fully-wound, half run-down, almost due for re-winding, or actually being re-wound. There are several other devices, of great complexity, which render the machine entirely unique—but I will not bore you with an account of these, further than to remark that No. 3 embodies, among its minor refinements, two sets of roller-bearings—steel rollers pivoted into a revolving cage and running on a steel race—which, although made about 1750, look as if they had been taken out of a modern car. It is interesting to note, by the way, that similar bearings are to be found in a very elaborate clock which Harrison built while engaged on No. 3, and which he used to regulate all his later timekeepers. Its general mechanism follows No. 3's very closely—although, of course, it is controlled by a pendulum, and not by balances—and exhibits the same refinement of detail.

By 1757, No. 3 was so nearly finished that Harrison notified the Board of Longitude that he proposed shortly to compete with it for the £20,000 reward; and he suggested, at the same time, that he should put in hand a much smaller timekeeper to serve as an auxiliary—as we should call it, a deck-watch. This proposal was approved, and with the help of his son, William, he constructed his celebrated "Watch" (No. 4)—the most famous timekeeper which ever has been or ever will be made.

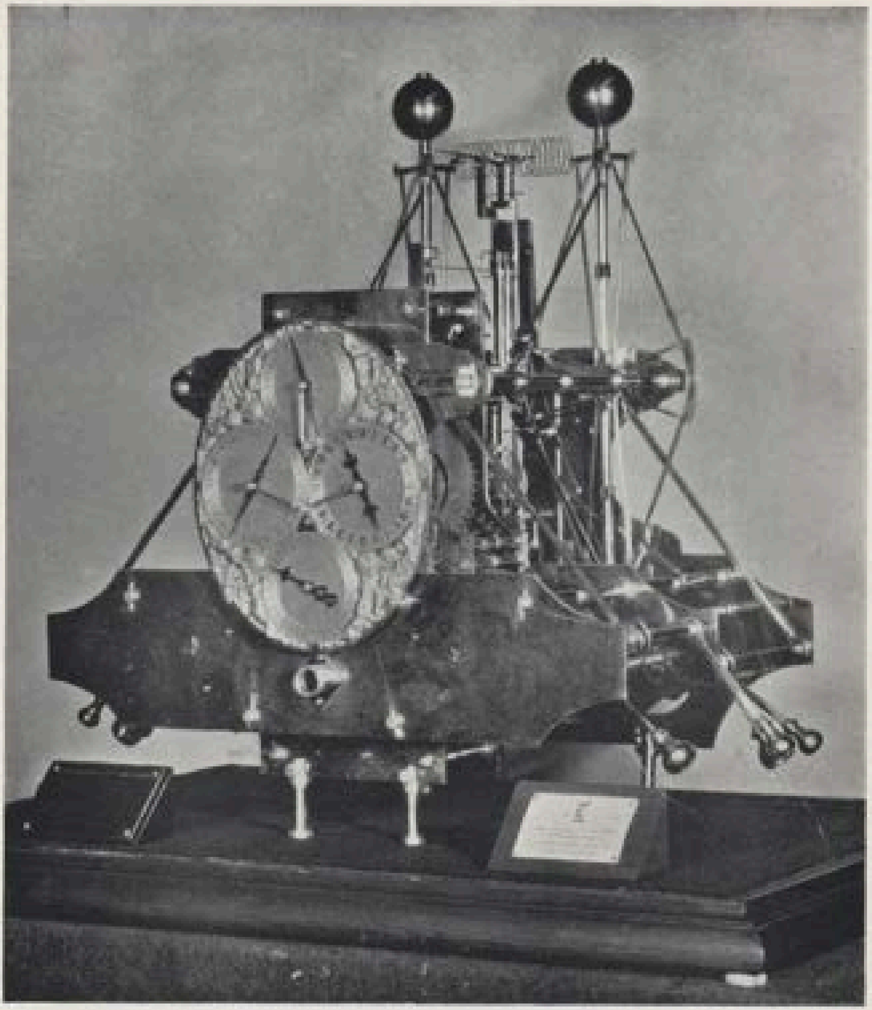
No. 4—which I now hold in my hand—is a very large silver watch (diameter 5.2 in.), resembling the ordinary "carriage-watch" of the period. In essentials, its mechanism is very similar to that of No. 3, with one exception—the escapement. The "grasshopper" could not conveniently be used in so small a machine, so Harrison fitted a much-modified and improved form of the common watch-escapement of his day (the "verge"). The "compensation curb" and spiral balance-spring of No. 3 are retained, as also the remontoire (here re-wound every 7½ seconds). An unusual feature of the dial is a centre-seconds hand, revolving between the other two.

Although Harrison originally regarded No. 4 as of secondary importance compared with No. 3, an unpublished description of his mechanism which he wrote in 1763, and of which I possess a copy, shows the almost incredible pains which he lavished on its design, construction and adjustment. And he may not, therefore, have been altogether surprised when, on test, it showed itself fully as accurate a timekeeper as No. 3, while possessing the great advantage of being very much more portable. In consequence, No. 3 was shelved (it was never tried at sea, although it once got as far as Portsmouth) and Harrison "declared to win" with No. 4 alone.

The new timekeeper's first official trial took place in 1761, when William Harrison embarked with it in H.M.S. *Deptford* at Portsmouth, sailing thence for Jamaica on November 18th. Captain Digges of the *Deptford* shaped course to touch at Madeira, and after nine days out of sight of land the ship's longitude, by dead reckoning, was 13° 50′ W. (from Greenwich), while by No. 4 it was 15° 19′ W. Digges, naturally, was inclined to favour the dead-reckoning, but William Harrison maintained very forcibly that the timekeeper was correct, and that if Madeira were correctly marked on the chart they would sight it the following day. Accordingly Digges, although offering to bet five to one that No. 4 was wrong, held on his course—and sighted Madeira next morning (December 9th). This greatly relieved the ship's company, who feared that they might miss the island altogether, " . . . . . the consequence whereof", as a contemporary account put it, "would have been Inconvenient, as they were in Want of Beer". You will remember that, in those days, water could not be kept fresh for long at sea, and that the seaman received a ration of either beer or wine—hence the popularity of Madeira as a point of departure. Light is thrown on the *Deptford's* difficulties by a note in her log (December 7th) "Condemned by Survey 1057 Galls. Beer, 480 pds. cheese, which was thrown in the Sea", while her Master's journal for December 9th mournfully records, "This day the Ship's Beer is all expended, the People oblidged to drink water". However, relief was close at hand. On arrival at Madeira we read "Received 3 Pipes of Wine for the Ship's Company", and again "Received 9 Butts of Wine and stowed it away".

On reaching Jamaica (January 21st, 1762) No. 4's error, after allowing for its rate of going, was found to be 5 seconds slow, corresponding to 1¼′ of longitude—or, in the latitude of Jamaica, something less than 1 geographical mile. Accordingly, under 12 Ann. cap. 15, Harrison was entitled, provided he could show that his timekeeper constituted a "generally practicable and useful" method of finding longitude, to a reward of £20,000. To this he was not only legally, but morally, entitled—for the great and famous problem, which had baffled Newton, Halley, Leibnitz, and a hundred others, was definitely solved at last.

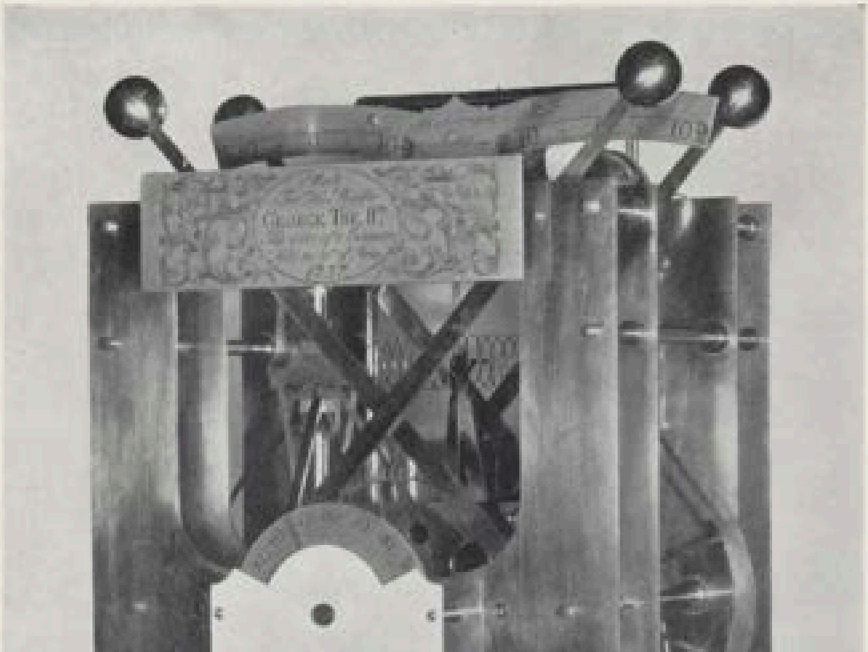
This, however, the Board of Longitude were slow to admit. They advanced Harrison £2,500 on account, but declined to pay the balance of the reward until after further trials, basing their action on the technical grounds that the longitude of Jamaica was not known



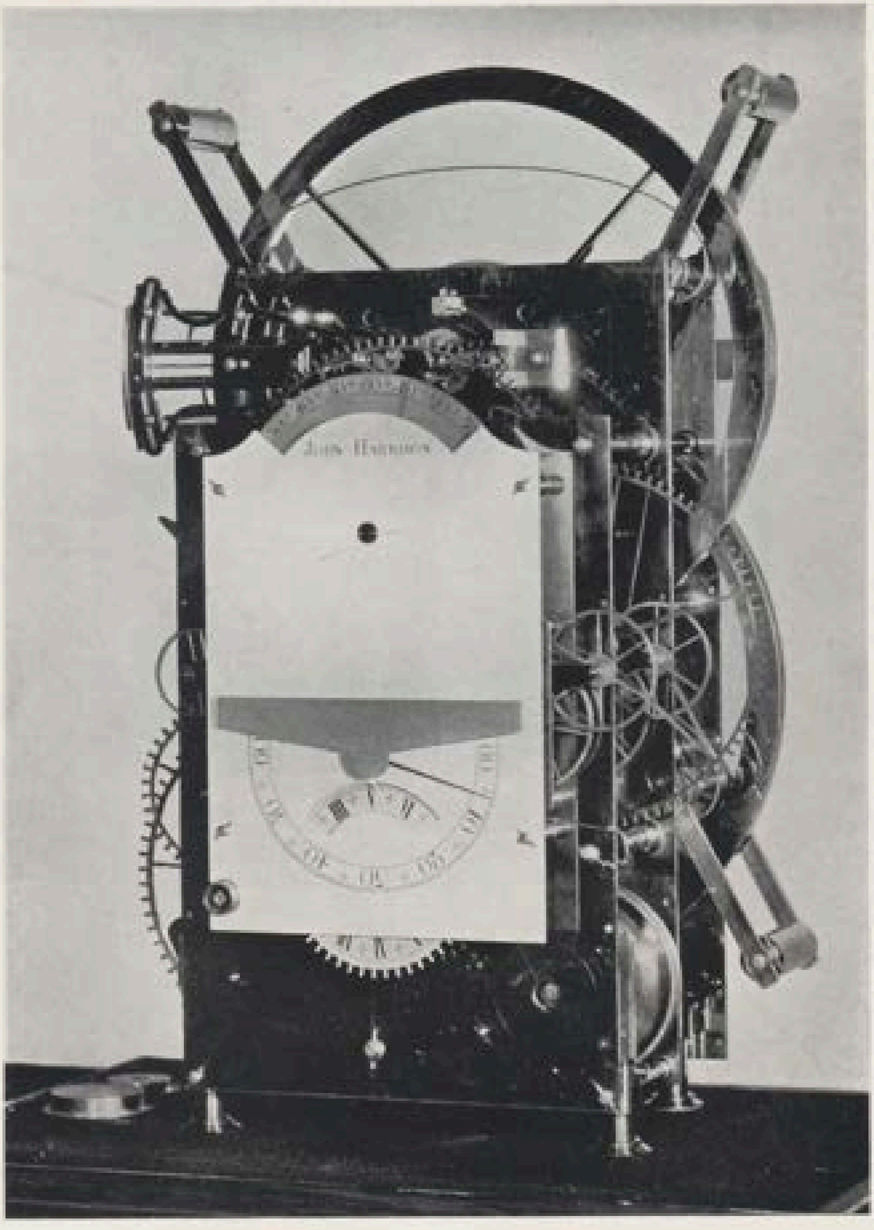
HARRISON'S No. 1 TIMEKEEPER

Navigation Room, National Maritime Museum

Plate II



HARRISON'S No. 2 TIMEKEEPER
Navigation Room, National Maritime Museum



HARRISON'S No. 3 TIMEKEEPER
Navigation Room, National Maritime Museum

Plate IV

HARRISON'S No. 4 TIMEKEEPER, WHICH WON THE £20,000 REWARD

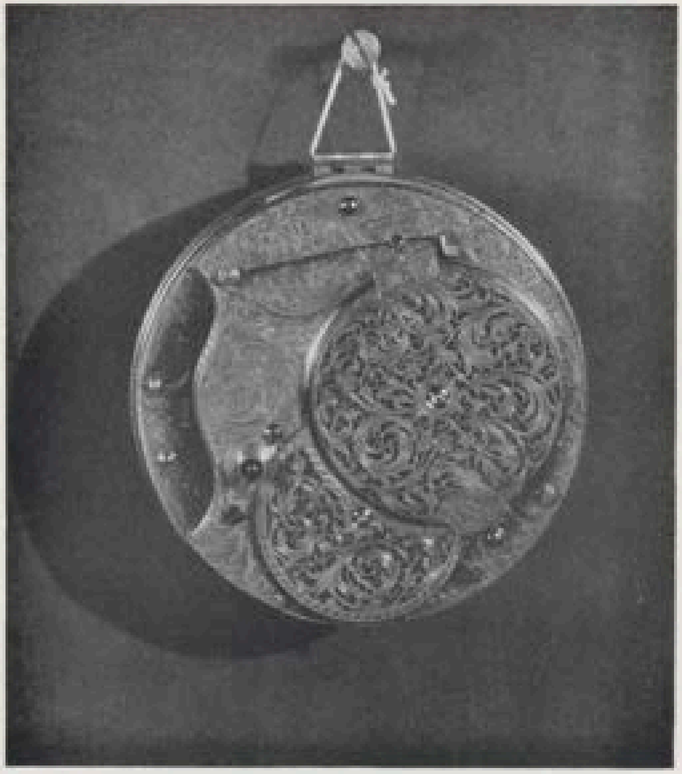
Navigation Room, National Maritime Museum

Plate V

DUPLICATE OF No. 4 (K 1) MADE BY LARCUM KENDALL AND USED BY CAPTAIN COOK
Navigation Room, National Maritime Museum

Plate VI

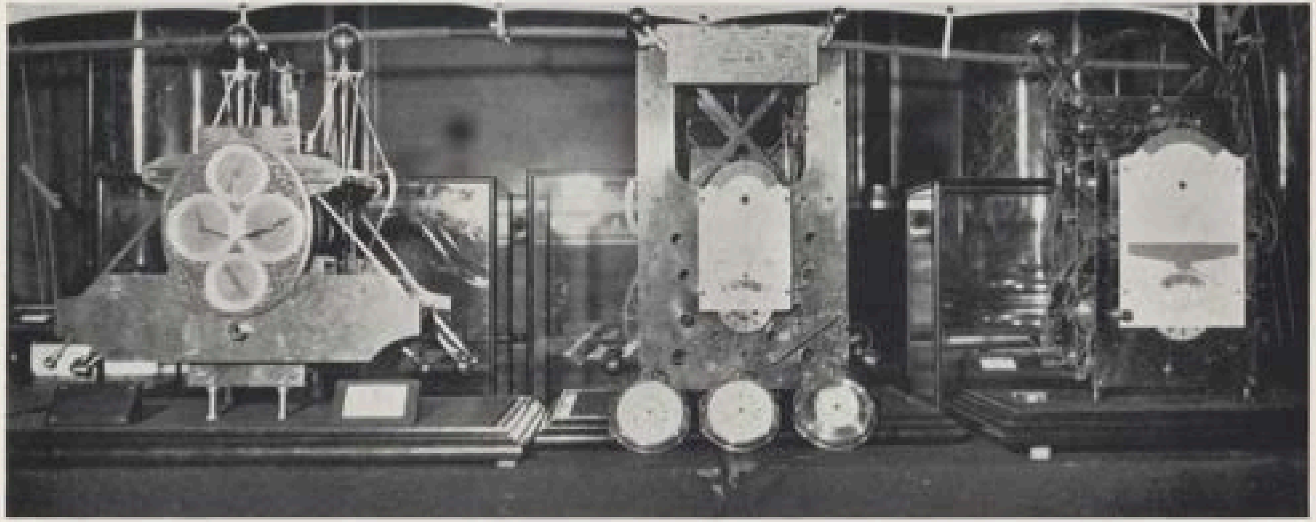
HARRISON'S No. 5 TIMEKEEPER
Guildhall, London; Worshipful Company of Clockmakers



TOP-PLATE OF K 1

Navigation Room, National Maritime Museum

Plate VIII



THE HARRISON TIMEKEEPERS ON EXHIBITION AT THE DRAPER'S HALL, FEBRUARY 21ST, 1935
AT BACK: No. 1, No. 2, No. 3 IN FRONT: K 1, No. 4, No. 5
(By courtesy of *The Times*)

precisely enough to afford an accurate standard of time for comparison with that shown by No. 4, and that the method employed at Portsmouth to obtain the latter's rate of going was untrustworthy. They seem to have suspected that the astonishing accuracy of the timekeeper's going was only apparent—that, if not entirely accidental, it had partly resulted from some fortuitous compensation of errors.

After much delay and wrangling, a second official trial took place in 1764. William Harrison, with No. 4, was despatched in the *Tartar* to Barbados, accompanied by two official observers—Nevil Maskeylyne, shortly to become Astronomer-Royal, and Charles Green, an assistant at the Royal Observatory who afterwards accompanied Cook on his first great voyage and died of dysentry on the way home. They were instructed to determine the longitude of their observation-spot at Barbados *de novo*, by astronomical observations, and compare the result with the longitude given by No. 4. This they did, with the result that the timekeeper's error was found to be 38.4 seconds fast (in seven weeks), corresponding to 9.6 geographical miles. Moreover if allowance were made, during the whole out-and-home voyage, for the slight changes of rate in different temperature declared by Harrison beforehand, No. 4's total error would be reduced to a loss of 15 seconds in five months, or an error of *less than one tenth of a second per day*. Harrison had written (in the MS. already mentioned):

> I think I may make bold to say, that there is neither any other Mechanical or Mathematical thing in the World that is more beautiful or curious in texture than this my watch or Timekeeper for the Longitude . . . . and I heartily thank Almighty God that I have lived so long, as in some measure to complete it.

And, assuredly, his pride in his masterpiece was fully justified.

The Board of Longitude, however, were still inclined to be sceptical. Before they would pay another penny, they insisted that Harrison should make a full disclosure, on oath, of No. 4's mechanism and construction to a committee which included three watchmakers; and also hand over to the Board, in trust for the public, all four of his timekeepers. They would then pay him an additional £7,500; making in all, £10,000. But they flatly declined to pay the second half of the reward unless and until he made two more timekeepers, and submitted them to such tests and official trials as they might see fit to impose. It should be noted that Harrison was then over *seventy*, and that his sight was failing.

Eventually, Harrison—finding, as he remarks, that otherwise he would get nothing at all—complied with the Board's conditions so far as the first half of the reward went, and was paid his £7,500 (October 28th, 1765). The second half, he regarded as lost to him for ever—and, it must be admitted, with reason. The stipulation that he, himself, must make two more timekeepers was both onerous and futile—it would have been far more to the purpose if these had been made, at the Board's expense, by different workmen under Harrison's direction. In fact, the Board seem to have had an inkling of this themselves; for, having made No. 4 their property—in trust for the public—they commissioned Larcum Kendal, a well-known London watchmaker, to construct an exact duplicate of it. Incidentally, they had previously sent No. 4 to the Royal Observatory, where it underwent a twelve months' trial under Maskelyne's supervision.

When the results of this trial, which were not very good, were published, Harrison—aided by his friend James Short, F.R.S.—replied in a pamphlet which is perfectly sound on the mechanical issues involved, but makes some unfair allegations against Maskelyne's personal character. Maskelyne was an honourable man with a strong sense of duty—on the other hand, it cannot be denied that he was strongly in favour of the method of lunar distances, and that he disliked timekeepers in general and No. 4—together with its maker—in particular. Whether by accident or design, his conduct of the trial was not calculated to exhibit No. 4's merits in a correct light; and he deduced from it the quite ridiculous conclusion—utterly exploded by the two previous trials at sea—that the timekeeper could not be relied upon to within 1° of longitude within the course of a six weeks' voyage!

If further disproof of this absurd contention were needed, the remarkable performance of Kendall's duplicate (K 1)—which I have here—supplied this in abundance. Completed in 1770, it went to sea with Cook in his second (Antarctic) voyage, 1772-1775. During three years of strenuous service, in which tropical heat alternated with extreme cold, and flat calm with furious gales, it went so well that Cook, the most exact and least enthusiastic of men, had nothing but praise for it. While at first sceptical of its value he soon begins to refer to it, in his journal as "our trusty friend, the Watch", and "our never-failing guide". He made a special point, too, of asking for it to be re-issued to him for his third voyage. Here is a specimen of its accuracy. In 1773, Cook, during his second voyage, discovered Hervey I., and determined its longitude—based on that of Tahiti, as transferred by K 1—to be 158° 54′ E. In 1777, during his third voyage, he made the island again, and re-determined its longitude—again by K 1, but based this time on that of Queen Charlotte's Sound, N.Z.—as 159° 04′ E. In the latitude of Hervey I., the difference is roughly nine geographical miles.

But I must return to Harrison. In spite of age and infirmities, he and his son managed to complete, in 1770, a fifth timekeeper—which you see here. It is essentially a duplicate of No. 4, but is practically devoid of ornament, and has one or two slight mechanical improvements. It was tried on shore, with great success, in 1772—but not at Greenwich.

Harrison had at last found a patron—the most powerful in the Kingdom. The published accounts of the *Tartar's* voyage, and of the subsequent proceedings in connection with the great reward, had attracted King George III's attention, and in due course the two Harrisons were granted an audience at Windsor. The old man told the long story of his struggles, first with mechanical difficulties, and then with officialdom, to a sympathetic listener—for King George always had a warm corner in his heart for scientific men. He was heard to remark, *sotto voce*, "These people have been cruelly wronged", and then, explosively, "By God, Harrison, I'll see you righted"! And forthwith he ranged his social and Parliamentary influence on Harrison's side.

As a first step, No. 5 was tested at the King's private observatory (Kew). In ten weeks, its total error on mean time was only 4½ seconds (it is probably the best of all the Harrison machines as a time-measurer, though I doubt if it ever excelled K 1 in this particular); but the Board of Longitude declined to receive any particulars of the trial, as not having been made under their direction. In consequence, Harrison petitioned Parliament—and, greatly to their surprise, the Board found themselves on the defensive. Questions were asked—very harsh questions, and very difficult to answer. Copies of all the Board's minutes relating to Harrison were extracted from them, and laid on the Table. It appeared likely that a day would be assigned for their examination by a Committee of the whole House. The Board bowed to the storm—and they seem to have offered little or no opposition to the insertion in a General Supply bill (13 Geo. III, cap. 77) of a clause which granted Harrison, without any further delays or trials, the second half of the reward which he had most justly won.

But, even then, they managed none the less to bilk him—there is no more expressive word—of a considerable sum. Many years earlier, they had advanced £1,250 for the construction of Nos. 2 and 3—on the understanding that, when the machines were completed, they should become the Board's property (in trust for the public). The machines had been constructed, and they had also been surrendered to the Board; in 1765, when Harrison received the first half of the reward. Most men of common sense, therefore, would regard the transaction as closed; but in so doing they would underrate the Board's resourcefulness, while over-estimating its honesty. By entering a caveat at the last moment, the Board secured £1,250 out of the second £10,000, Harrison being paid £8,750 only. In other words, after paying £1,250 for two timekeepers, the Board not only received these machines but also every penny of their money back again! It is unnecessary for me to comment on this transaction—and any comments of mine which were strong enough to do it justice would not, I fear, be quite suited to a mixed audience.

However, Harrison had won his fight, and could now take his rest. In the three years of life which were left to him he did little beyond publishing an extraordinary pamphlet (on time-measurement) which, unlike others to which he put his name, was his unaided work—and which is nearly unreadable. It affords ample proof of what was often said of him in his lifetime, that he could do, but could not describe. All his life, he was almost incapable of expressing his mechanical ideas with any clearness, either verbally or in writing.

He died at his house in Red Lion Square on March 24th, 1776, in his eighty-third year, and was buried on the south side of Hampstead parish church. William Harrison died in 1815.

Now I should like to trace, for a few minutes, the later development of the marine timekeeper. Although No. 4, so far as performance went, left little to be desired, its complication and consequent high price (Kendall charged £450 for K 1) would always debar such machines from general use. The Board of Longitude, indeed—still smarting from their recent contest with Parliament—affected to regard the problem of finding longitude at sea as entirely unaffected by Harrison's labours; and they procured the passage of an Act (14 Geo. III, cap. 66) which offered a further reward of £10,000 for any method of determining a ship's longitude within half a degree at the end of a six *months'* voyage. This reward, by the way, was never won—the Act was repealed when the Board of Longitude was abolished, not before its time, in 1828—but it is amusing to note that K 1, in the Board's own possession, was fully capable of complying with the Act's requirements.

Under the conjoint stimulus of Harrison's example—and success—and that of a second "glittering prize", the professional watchmakers awoke from their long slumber and set themselves to make marine timekeepers. Larcum Kendall was first in the field, and seemed marked out as Harrison's legitimate successor—Harrison himself being *hors concours*, and his son's attention directed elsewhere. But while Kendall was a splendid workman, he had little creative ability—though he made two attempts to simplify No. 4, he only produced two rather indifferent timekeepers. He also made one or two beautiful little pocket-chronometers, with spiral compensation curbs and a form of the "échappement Robin" (so-called, although Robin certainly did not invent it); but, in general, his work on marine timekeepers is of slight importance.

Much the same must be said of a very great English horologist—Thomas Mudge, a man of immense talent and most amiable character. Most of you are, I expect, carrying a memorial to him in your pockets; for he was the inventor of the detached lever escapement, used in practically every watch which has been made for very many years past. He was a member of the committee before whom Harrison took No. 4 to pieces in 1765—and his mind seems to have then acquired a bent in favour of Harrison's mechanisms which it never lost. His timekeepers—he made three—are, really, over-complicated exaggerations of an already over-complicated original. I have no time to describe their mechanism, or to dilate on their workmanship—which is simply exquisite—but it is worth noting that although Maskelyne, as the result of repeated trials at Greenwich, had no very high opinion of their accuracy, the performance of the first machine in its second trial (1776-1778), if computed by modern methods, would have yielded a "trial number" of 11.73, a standard not reached again at Greenwich until 1873. After competing three times, unsuccessfully, for the £10,000 reward, Mudge was granted £2,500 by Parliament in 1793, although the Board of Longitude were opposed to this course. He died in the following year.

But to find the first real advance upon No. 4, we must cross the Channel. In 1766 Pierre Le Roy of Paris, "Horloger du Roi", presented to the Académie des Sciences a marine timekeeper of his own design and construction, containing all the essential features of a modern chronometer—a detached escapement giving direct impulse to the balance, isochronised balance-spring, and compensation balance. All three of these devices are to be found in every chronometer made today—all three are present in Le Roy's machine—and the three are not to be found, combined or even separately, in any timekeeper of earlier date. Accompanying the machine was a memoir describing, in most lucid style, the principles of its construction and the calculations on which its proportions were based. On the joint evidence of machine and memoir, I regard Le Roy as the greatest horological genius who ever lived; but his labours—at once copied by his rivals—met with little or no recognition. And he seems to have been entirely lacking in that sheer grit and driving-force for which Harrison is so remarkable. Le Roy produced a duplicate of his machine in 1767, and both were tried at sea with considerable success—but thereafter he seems to have abandoned further effort, and to have preferred making expensive clocks and watches for wealthy customers. He died in 1785.

Contemporary with Le Roy was his great rival Ferdinand Berthoud—a Swiss who spent most of his life in France. He was the exact antithesis of Le Roy—a talented plodder, plentifully endowed with perseverance and self-confidence. Unlike both Harrison and Le Roy, too, he was a shocking sailor—as the result of accompanying his first marine timekeeper on a short trip, he returned more dead than alive—and some of the grosser defects of his early machines may charitably be attributed to this inability to study conditions at first hand. For the rest, they were partly unintelligent copies of Harrison's early machines, and partly *sui generis*—one was controlled by a pendulum, while his No. 8 machine appears, at first sight, to combine most of the features that a marine timekeeper ought not to possess. For example, it is driven by a falling weight; its escapement is undetached, and involves considerable friction; and it is compensated for temperature by a very roughly arranged "gridiron". Yet, strange to say, extended tests at sea showed that it was quite a reliable timekeeper.

However, while affecting to decry Le Roy's work, Berthoud was shrewd enough to appreciate its importance—and he gradually began to evolve machines bearing a colourable resemblance to the modern chronometer. His work was continued by his nephew Louis; while mention must also be made of another Parisian who is world-famous—Abraham Louis Breguet. Breguet (1747-1823) is responsible for a number of chronometers, whose beautiful finish is fully worthy of his reputation as the Stradivarius of watch-making—but he outrivalled Berthoud himself in the variety of his conceptions, and it is hardly an exaggeration to say that no two of his productions are exactly alike. A small chronometer of his making, preserved in the Arts et Métiers, is remarkable for having a glass balance-spring—the earliest example known. At first sight, it would seem that a glass spring—a mere rope of sand—would be hopelessly unsuited to marine use; but such springs are surprisingly strong and durable, while they are much less affected by temperature changes than either steel, gold of palladium spring. Scarcely any chronometer maker, however, has cared to fit them, while the introduction of "elinvar"—a nickel-steel alloy whose coefficient of expansion is practically negligible—has rendered them of purely antiquarian interest.

But while the French chronometer-makers who followed Le Roy unquestionably produced a considerable number of excellent marine timekeepers differing widely in details (and even in type), their contemporaries in this country performed a much greater service by evolving a simple, accurate and efficient chronometer which could be produced in large quantities at a comparatively low price. Foremost among them are John Arnold and Thomas Earnshaw, both of whom are in the direct line of descent from Le Roy—although I think that his direct influence upon them was very slight. It should be added that they were no better friends than Le Roy and Berthoud, and that they jealously disputed the originality of each other's improvements.

Arnold, the elder of the two (1736-1799), had a varied career before settling in London, where he prospered as a watchmaker and turned his attention to chronometers. Three of his early machines were carried in Cooks' second voyage, and performed very badly. But, nothing daunted, he profited by his mistakes—and in a few years he had established a chronometer factory and was turning out satisfactory machines by the hundred.

Pride of place, however, as between Arnold and Earnshaw, must go to the latter (1749-1829). The Arnold chronometer was an excellent instrument; but Earnshaw's was even better, because simpler. So admirable was it, in fact, that it became the type which all succeeding chronometer-makers have followed. If I were to show you, side by side, an Earnshaw chronometer of 1795 and one made this year, you would be puzzled, I think, to discover any material difference either in their appearance or their mechanism—a very remarkable tribute to the mechanical sagacity of a man who died more than a century ago. Earnshaw's labours are fittingly commemorated by a tablet affixed (on the occasion of his centenary) to the wall of St. Giles Church, Holborn (where he is buried) and recording the fact that he was "the Creator of the Modern Marine Chronometer".

I should add that in 1798 and succeeding years Earnshaw made three determined attempts to win the £10,000 reward offered in 1774; and that although he failed, the circumstances of his failure, and the very narrow margin which finally divided him from complete success, showed clearly that in his day he had no equal as a chronometer-maker. As a partial solatium, he was granted £3,000 (less certain interim advances) by the Board of Longitude in 1805, a similar gratuity being paid at the same time to Arnold's son in recognition of his father's labours.

I want now to tell you something of the later history of the pioneer machines—the Harrison timekeepers; and I must apologise if, in so doing, I seem rather egotistical. It so happens that through force of circumstances I have had more to do with those machines than any one else except their maker.

The extant Harrison machines connected with the finding of longitude at sea are six in number—the five marine timekeepers and the clock by which he regulated them. It will be convenient to take the last-named first.

The clock descended to Harrison's grandson, John Barton of the Mint, who presented it, about 1840, to the Royal Astronomical Society. It was kept going until about 1865, after which it stood for many years—being, however, cleaned and again set going, as a labour of love, by Mr. E. T. Cottingham in 1909. Unfortunately, it was damaged a few months later by an unskilful attempt to set it going after it had stopped for want of winding, and it remained in that state until, with the Society's permission, I cleaned and repaired it in 1927-29. It has since been going very regularly. For example, on December 27th, 1934, it was 34 seconds fast—on February 11th, 1935, it was the same—and at no time between those two dates had its error, as determined by the hourly time-signals, varied appreciably from that 34 seconds fast. No doubt this result was partly due to an accidental compensation of errors—still, I think it indicates that the clock, in spite of its complication (it has 540 separate parts) and its early date (about 1745) must have been, and still is, a remarkably good time-measurer. Like the three large marine timekeepers, it requires no oil in any part.

Harrison's fifth timekeeper, like the clock, remained in private hands. Part of its history is obscure—but at the sale of the Napier collection it was bought by the Clockmakers' Company and has since been in the museum at the Guildhall. I first saw it there in 1921, and discovered that it was out of order, the remontoire being deranged. I managed to rectify this without taking it to pieces, and it has been in going order since—I re-started it without difficulty this morning.

The first four timekeepers became the nation's property in 1765. No. 4 was immediately sent to Greenwich—the three large machines remained in Harrison's house until May 23rd, 1766, when Maskelyne called for them in person, and removed them to the Observatory in a springless cart. Incidentally, he and his workman managed to drop No. 1 on the stairs, which did it no appreciable good.

Once at Greenwich, the three big machines fell into a state of disrepair and corrosion. This was not due to any actual want of care on the part of their custodians—I should like to make that point quite clear—but was a natural consequence of the very peculiar combination of qualities which they presented. They were very bulky—they were very heavy—they were very complicated—and they were very fragile. Moreover they were bolted into cases which were also exceedingly heavy, and which gave very little clue to the nature of their contents. In addition, they had been rendered obsolete by the success of the obviously more suitable No. 4—and they naturally came to be regarded as mere curiosities, not far removed from nuisances. Maskelyne, too, interpreted his duties as their custodian so rigorously that during his tenure of office (he died at the Observatory in 1811) he would hardly ever allow their cases to be opened.

In 1836 the forlorn condition of the machines aroused the practical sympathy of E. J. Dent—then in partnership with the younger Arnold, and afterwards founder of the present firm of Dent & Co. He offered to clean the machines, gratuitously; and his offer was accepted. Arnold & Dent's workmen spent four years on the job—and, so far as I know, they did it thoroughly. They did not, however, attempt to restore the machines to going order; and when they found parts, such as the wooden pallets, broken, they trimmed them off to look neat—which gave me, later, a good deal of trouble, as I was left with no indications as to the size or shape of the missing portions. I think, too, that they managed to mislay a good many parts of No. 1 in the interval between dismantling and re-assembling it.

When the machines were returned to the Observatory in 1840, Arnold & Dent sent with them a number of drawings of their mechanisms. The drawing of No. 1 are fragmentary (about half are missing); those of No. 2 (by Thomas Bradley) are the most elaborate and beautiful mechanical drawings that I have ever seen; and those of No. 3, although more roughly executed, are quite complete in detail. But occasionally one finds in all the drawings definite indications (springs coiled the wrong way, etc.) that they were made from machines which were no longer in working order, and whose functions were not thoroughly understood. I ought to mention, by the way, that Harrison left no drawings or descriptions of Nos. 1, 2 or 3; and that while his two descriptions (one published, the other in MS) of No. 4 and his drawings for it are still extant, the descriptions are hopelessly obscure, and the drawings almost equally so.

If the big machines, after their overhaul in 1836-1840, had been put into airtight cases, much trouble would have been saved—I speak feelingly on this point. But they went back into their original receptacles, and the process of decay began again. When I first saw them in 1920, none was in going order—not even No. 4, which had been cleaned in 1890 for display at the Naval Exhibition. All were dirty, defective and corroded—while No. 1, in particular, looked as though it has gone down with the *Royal George* and had been on the bottom ever since. It was completely covered—even the wooden portions—with a bluish-green patina.

I could not bear to see them in this condition. It seemed to me such a futile, tragic ending to a great adventure. They were the first accurate marine timekeepers ever made—the life-work of an original genius who was also an Englishman—and here they were; discarded . . . forgotten . . . buried. Surely, they deserved a better fate. Yet, little as I then knew about them, I could see that even to clean them would be a tremendous job—one for which a chronometer-maker, if one could be found willing to undertake it, would probably make a charge running into hundreds of pounds, if not into four figures. There was no likelihood that such an expenditure of public money would be sanctioned; nor could I afford to pay the required sum out of my own pocket.

There was, however, an alternative—and that was, if I could obtain permission, to do the work myself. True, I had had no horological training—but I reflected that, so far as that went, Harrison and I were in the same boat; and that if I started with No. 1 I could scarcely do that machine any further harm. I obtained permission to clean it; and in June, 1920, I began operations by removing it to my workshop and getting about 2 oz. of dirt and verdigris off it with an ordinary hat-brush.

I then took it to pieces as far as possible, and cleaned every part separately—these being then lacquered to prevent future corrosion. After re-assembling it—the whole work occupied about a year—I sought permission to restore the many missing parts, and get it going again. But, in those days, the authorities thought it best that no new parts should be put into the machine; and although I was somewhat disappointed at the time, I recognise now that this decision was a blessing in disguise. In 1921, I did not know nearly enough about Harrison's mechanical ideas—and while I should probably have managed to make No. 1 go, I should have had to introduce several devices which Harrison did not employ. In consequence, No. 1 went back to Greenwich (in an airtight case) clean, but not in going order—and remained thus for ten years.

I next tackled No. 4. I should explain that I cleaned No. 1 at my own expense—but thereafter the Observatory insisted on paying my out-of-pocket expenses. No. 4's mainspring was broken, the remontoire disarranged, and the escapement wrongly set—in addition, it was very dirty. I took it apart with some difficulty. It took me three days to learn the trick of getting the hands off—I more than once believed that they were welded on—and about as long to dissect the remontoire. After cleaning every part I procured a new mainspring and set myself to re-assemble the machine, working by trial and error. After about a year's work in all, No. 4 was again clean and in going order, and has so remained ever since; but, if kept going, it will have to be cleaned and re-oiled every two years—so will K 1. That is on account of the gradual drying of the oil in the pivot-holes.

I then turned my attention to No. 2. Of the three big machines, this was in the best condition (which is not saying very much) and had comparatively few parts missing. Admittedly, it is complicated; but its considerable size makes dissecting it a comparatively straightforward job, provided that—as I always have done—you keep accurate notes and drawings, in minute detail, of how all the parts are arranged, and of the order in which they have to be removed. The same routine was followed as in previous cases—the machine was taken entirely to pieces, all parts thoroughly cleaned, defective parts repaired, missing parts re-constructed, and the whole re-assembled; the adjustment of the various parts being then determined by a long process of experiment. The whole work occupied about a year, after which I had the pleasure of seeing it going once more. I well remember how delighted I was when I first got it to go for eight hours consecutively. It has now been going continuously for *ten years*—it was exhibited at Wembley in 1925, and has since been on view, until a few days ago, in the Science Museum, South Kensington.

The next machine to be taken in hand was No. 3. This, as I mentioned earlier, took Harrison seventeen years to construct—and it took me seven years to repair. I don't, of course, mean that I worked at it for that period continuously—the work was twice interrupted for various reasons, chiefly my own ill-health; but I began it in 1924 and did not complete it until 1931.

The delay was due, in great measure, to the machine's almost complete inaccessibility. Consider the two escapements. When they are in position, you can just touch the upper escapement, but you can do nothing with it; and you can't even touch the lower—it is entirely boxed in with other mechanism. If you wish to determine—as I had to do—the length of the pallets, the process is roughly as follows. You start with the escapements out, and fit your experimental pallets, setting them to some arbitrary length. You then put them into the machine, and replace the parts you had to remove to get them in. That takes about four hours. You then make your tests, which may take a minute or so, and discover that some adjustment is required. To make that adjustment, you must take the escapements out again, which takes another four hours—and the same time must be spent before you get them back in place and are ready to make a fresh test. In all, I suppose I had those escapements in and out forty times, at eight hours a time—and since there were many other similar jobs to be done in this tentative way, the enormous time which the machine's reconstruction occupied is, perhaps, not altogether surprising.

Moreover, No. 3 is not merely complicated, like No. 2—it is abstruse. It embodies several devices which are entirely unique—devices which no clockmaker has ever thought of using, and which Harrison invented as the result of tackling his mechanical problems as an engineer might, and not as a clockmaker would. It became necessary to determine, first, what these devices were intended to do; secondly, how they were designed to do it; and, thirdly, what parts of them were missing—the situation being complicated by the fact that, in more than one instance, remains of some device which Harrison had tried and subsequently discarded had been left *in situ*. However, I gained ground slowly but surely, feeling my way as I went—and on March 8th, 1931, No. 3 was once more clean, complete and going.

There was not much left to do. The R.A.S. clock was going. Nos. 5 and 4 were in going order, although not kept going. Nos. 3 and 2 were going. No. 1 was clean—if I could get it going again, my work would be done. On application, I received permission to re-construct it, and get it going *if I could*—a point on which I entertained a modest confidence which no one else, I think, shared.

The job certainly looked pretty formidable—particularly since, as Sir Boyle Roche might have put it, there were enough missing parts to fill a bucket. There were no main-springs, no mainspring-barrels, no chains, no escapements, no balance-springs, no banking-springs, and no winding gear. One of the eight long balance-bearers was gone, and another had shed its counterpoise. Five out of the twenty-four anti-friction wheels had vanished. Many parts of the complicated gridiron compensation were missing, and most of the others defective. The seconds-hand was gone and the hour-hand cracked. As for small parts—pins, screws, etc.—scarcely one in ten remained.

Quantitatively, most of the machine was still there—some 66 lb. out of a total 72 lb. or so—and in most cases I was able (the machine being practically symmetrical about a central plane) to duplicate a missing part from its survivor opposite. Failing this, it was generally possible to determine its size, shape, etc., on general principles. Early in 1933 I was ready to start re-assembling the machine (all of whose parts had now been polished and re-lacquered) with fair confidence that every missing piece, down to the smallest pin and wire, was again present—and that I could show some sort of authority for the shape, size and fitting of each of them.

The assembling was not particularly easy—still, coming to it after my prolonged struggle with No. 3, I took it more or less in my stride. The worst job was the last—adjusting the little steel check-pieces on the balance-springs; a process which I can only describe as like trying to thread a needle stuck into the tailboard of a motor-lorry which you are chasing on a bicycle. I finished this, with a gale lashing the rain on to the windows of my garret, about 4 p.m. on February 1st, 1933—and five minutes later No. 1 had begun to go again for the first time since June 17th, 1767: an interval of 165 years.

It will never, I'm afraid, be an accurate timekeeper again, for the rods of the gridirons have distorted themselves in trying to expand and contract while rusted together—and although it would not be very hard to make and fit new gridirons this would mean discarding, in its original form, the most striking feature of this extraordinary machine. In consequence, I left the original gridirons *in situ*. The new balance-springs, too, are a little too strong, and the machine goes somewhat slow for this reason. Still, as Galileo probably did not say, "E pur si muove"—all the same, it does go—and, if you had seen it as it was when I first saw it in 1920, you would, I think, have been quite sceptical that it could ever go again.

And that is the end of the story of John Harrison's timekeepers; but, before I conclude, there are two points on which I would like to touch as briefly as possible.

I should not like you to leave here under the impression that I did all the work of reconstruction single-handed. That is far from being the case—I have been considerably helped in several ways. I want, in the first place, to express my deep gratitude to Sir Frank Dyson—who was Astronomer-Royal when I began the work—for granting me permission (largely, in the first instance, on my own recommendation) to clean and repair the Harrison machines; and both to him and to his successor, Dr. Spencer Jones—and also to Mr. Bowyer, of the Observatory—for the interest which they have always taken in the work, and the kindly encouragement which they have always shown me.

On the technical side, too, my thanks are due to three friends—all of whom are here today. When, in the course of the work, I wanted to have any large metal portions cleaned, polished and lacquered, I took them to Mr. Buck, of the Gold and Silver Plating Company—and I always got them back looking like new, and safeguarded against future corrosion. If there was any repair to be effected, or small part to be made, which I could not tackle with my rather limited resources—for I have never possessed a lathe, or a proper outfit of watchmaking tools—I would take it to Mr. Hopwood of Blackheath. He is a very practical watch and clock repairer; and I would always find that the repair was done, or the new part made to my design, in a style which would have fully satisfied Harrison himself. And, in connection with the re-construction of No. 1, there were several pieces of work—including the making of the new balance-springs and the new winding-gear—which were not only beyond my resources, but demanded those of a chronometer factory; and I accordingly entrusted them to Mr. Frank Mercer, of Thomas Mercer & Sons. I was not at all surprised that the work was beautifully done—the surprise came when I asked Mr. Mercer to let me have his account. I had sent in a rather modest estimate for the total cost of the whole work—in my anxiety to get every part of it done as well as possible I had (as I was gloomily aware) outrun the constable—and I imagined that when the Observatory had paid Mr. Mercer's bill I should find myself in debt to the Crown to the tune of perhaps £100—or, say, a year's pension. But when I asked Mr. Mercer how much was owing to him, he at once informed me that he considered the work to be of national interest, and that he did not propose to make any charge for it whatever.

I ought to mention, too, that a problem in connection with No. 1 which had puzzled me for ten years—the problem of how Harrison drove a single fusee with two mainsprings—was solved in about five minutes by my friend Mr. Courtenay Ilbert; and I should also add that when all the work on all the machines was finished the Admiralty—greatly to my surprise, for I had never expected so much as a farthing—very generously sent me £100.

And, lastly, there is a question of motive which I would like to explain.

I believe you will not mind my repeating that the work, so far as I was concerned, was voluntary, and that it took twelve years. Now twelve years are no small part of any lifetime, and the question may suggest itself to you—"Was it worth doing? Is it worth while to spend twelve years upon a few pieces of obsolete and over-complicated mechanism? Wasn't it rather a waste of time"?

Well, I faced that question before I began the work. I thought then that it was worth doing—and, in the years between, that conviction has only strengthened and deepened. I think today that it has been very well worth doing—and I should like to tell you why I think so.

What makes a man great? A man may be great in his aims, in his achievements, or in both; but, at least, it is fair to say that a man is truly great who makes the world his debtor—who does something for the world which the world needs, and which no one before him has done or known how to do. And if we apply that criterion to the work of John Harrison, we can only come to one conclusion—that he was a truly great man.

He made the world his debtor because he showed the world—what it did not then believe—that Man could make a machine which would keep time at sea so very accurately that, by its means, he could determine a ship's longitude. He showed that in the most convincing fashion possible: by successively inventing, constructing and exhibiting five accurate marine timekeepers—machines such as the world had never seen before. That was a service to humanity in general, and to seamen in particular, which it is almost impossible to exaggerate. Even in these days of W/T there is not a seaman afloat, anywhere on the Seven Seas, whose track is not being made straighter, and safer, and more prosperous, by the possession of such a timekeeper. Judge, then, of the risks which seamen ran even so late as the middle years of the eighteenth century, when no practical method of finding longitude at sea was known at all—and when, as a direct result of that crying defect in ocean navigation, the sea took a dreadful annual toll of ships . . . and cargoes . . . and men's lives.

It was John Harrison—a landsman, a simple, self-educated Yorkshire carpenter—who first showed, at the price of fifty years' incessant thought and labour—labour conducted in the face of a complete scepticism, not confined to professional clockmakers but representing the informed scientific opinion of all Europe—single-handed labour, sustained only by an intense personal conviction that he would do what no man had ever done, and what no other man then believed ever would be done—it was John Harrison who, first of all men, showed the world that that annual tribute of ships, and treasure, and blood—that part of the heavy price of Admiralty—need be paid no longer . . . nor ever paid again. Such was this man's service to humanity: a man of whom we, both as his countrymen and as the world's greatest maritime nation, have much cause to think gratefully—and every right to be immensely proud.

If, then, we admit—as we must admit—that he was a truly great man, who well deserves to be remembered, what is the best way of remembering him—what is his best and most worthy memorial? Some might say that he ought to have a statue. I entirely agree—many men have been honoured with statues who haven't done a tenth as much for the world as John Harrison did. But I think that today we have a finer and more appropriate memorial than any statue could be—*and here it is*.

It is in our power, today, to take any one who wants to know more of Harrison, and Harrison's life-work, to the cases in which his machines are displayed. And we can say to them: "Here are the works of this man's hands and brain—complete, as he completed them—going, as he saw them go. We say that he was great—and here is the proof. Look—and judge for yourselves how great a genius this English carpenter must have been."

Admittedly, these timekeepers which Harrison constructed—wonderful though they are, both for the marvellous ingenuity of their mechanism and the beauty of their workmanship—these machines are obsolete . . . have long been obsolete . . . were obsolete even in Harrison's own lifetime. But the qualities which these timekeepers display in full measure—such qualities as vision and courage, self-denial and perseverance, resolution, endurance, and the will to win—those qualities can never be obsolete. They, in their nature, are immortal—and their manifest and abiding presence hallows these strange old machines.

They form, to my mind, the finest memorial that John Harrison could ever have; and for such a memorial, after all, twelve years' work is not a heavy price to pay. I shall always be proud that I have had the honour of being associated, to some extent, with the making of that memorial—and, if all the work had to be done again from the start, I would very gladly do it.

I thank you for listening to me so patiently.

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