The Early History of Chronometers: A Background Study Related to the Voyages of Cook, Bligh, and Vancouver

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The purpose of this paper is to outline the historical developments relating to the chronometer, which played so crucial a part in the voyages of discovery made by Cook, Bligh and Vancouver. The inventor of the first successful chronometer — a technological marvel of precision watchmaking — was John Harrison. His most famous model was the prize-winning H4 of 1759. Kendall's copy of this, known as K1, helped Cook to plot the first charts of New Zealand and Australia. K1 was also used by Vancouver, while K2 was once carried by Bligh on the *Bounty*.[1] It is generally well known that in 1714 the British Admiralty offered a prize of twenty thousand pounds (possibly a million dollars in modern terms) for a method that could determine longitude on board a ship to within half a degree (or approximately thirty miles) on a passage to the West Indies. It is, however, less well appreciated how important a part the need for determining longitude had already played in the process of developing accurate clocks and watches for use on land as well as on the sea.

Commander Waters has pointed out that "By about 1254 the Mediterranean seaman" knew his "direction between places to within less than 3° of arc", as well as his distances; "By about 1275 ... he had also a remarkably accurate sea chart of the whole of the Mediterranean and Black Sea coastlines", together with the sea compass and relevant table.[2]

Though there are claims that the sea compass was a European invention of slightly earlier date, Price feels that the use of the loadstone in navigation was probably of Chinese origin. Be that as it may, anyone who has sailed by the type of dead reckoning that can be used in the Mediterranean knows that — in addition to the charts (giving the bearings or winds), and an assessment of the ship's speed — the mariner requires a timekeeper unaffected by the motion of the sea. As long ago as 1306-13,

[1] The marine chronometers mentioned, together with H1 of 1737, are in the National Maritime Museum, Greenwich.

[2] D. W. Waters, "Time, Ships and Civilization," *Antiquarian Horology*, 4 (June 1963), p. 82.

BC STUDIES, no. 38, Summer 1978

Francesco de Barberino, an Italian poet, says that the careful mariner must have his *arlogio* as well as his chart and loadstone.[3] For such dead-reckoning navigation, timekeeping was provided at sea by the sand-glass.

It was once thought — and still is by some — that sand-glasses date back to classical antiquity. But Drover has pointed to the fact that — as with the weight-driven mechanical clock — there is no firm evidence that predates the early fourteenth century A.D. Our first dependable proof for the sand-glass is the figure of Temperance carrying what is very clearly such a timekeeper in a fresco by Ambrosio Lorenzetti (1338), of which there is a copy in the Science Museum, London. The first textual references for sand-glasses are to "xii orlogiis vitreis" in 1345-46, and "ung grant orloge de mer, de deux grans fiolles plains de sablon" in 1380.[4] Since all are called *horloges*, sand-glasses — like the water clocks of much earlier invention — can only be differentiated from mechanical clocks through the context. Unlike the mechanical clock, the sand-glass had the initial advantage that both the material and the technology for its relatively cheap production were easily available. As Drover puts it, "by the end of the fourteenth century the sandglass had become a familiar piece of household equipment . . . the making of the 'sand' was considered to be a routine affair for the housewife, and on a par with making jam or glue".

It will be noted that the two first textual references to sand-glasses are placed clearly within a context of them being made for taking to sea. There is evidence to suggest that sand-glasses may well have been invented for this purpose. Drover points to Italy as the source for both the sand-glass and the magnetic compass; he relates them to "the new techniques of navigation that developed in the Mediterranean".

During the fifteenth century — for reasons that include interference with the Eastern spice trade by the Turkish conquest of Constantinople in 1453, and the advances in navigation and ship design made under Henry the Navigator — Mediterranean seamen began to venture beyond their traditional waters. Navigation by dead reckoning was no longer good enough. This was particularly true of the trans-ocean voyages related to the exploitation of the Americas during and after the sixteenth century.

In conditions under which a dead-reckoning position could no longer be relied upon at sea, the main difficulty lay with determining the longi-

[3] C. B. Drover, "Sand-Glass 'Sand'," *Antiquarian Horology*, 3 (June 1960), pp. 62-67. See also C. K. and J. R. A. Aked, "Sand Glasses," *Horological Journal*, 120 (October 1977), pp. 3-10.

[4] Cited from Drover, "Sand-Glass," p. 62.

tude. The latitude, north or south, could most readily be determined by observing the height of the sun at noon, but to determine the longitude, east or west, on an earth that spins around its axis was a far more difficult proposition. As early as 1530, the Flemish scientist Gemma Frisius had recommended the use of a watch at sea for determining longitude, but until the advent of the pendulum no sufficiently accurate mechanical instrument existed. The principle, of course, is simple enough. If one sets a watch at the local time of one's home port, then every four minutes by which that local time differs from say the local noon time at sea represents one degree of longitude east or west of the home port. Beyond the technical problem of producing an accurate mechanical timekeeper was the further complication that time measurement itself, insofar as the public were concerned, had not been sufficiently rationalized. Despite North America's current wranglings over the metric system, we tend to forget how far down the road of rationalization in weights and measures we have now come. In time measurement, for example, when the voyages of discovery by Europeans began, the day, like the night, was still being divided into twelve equal parts. This meant that an hour at the latitude of Rome might vary between 45 and 75 minutes. At the higher latitude of London (51° N) the variation was even greater and the length of the day changed from 16½ to as little as 7½ hours. Clearly, although this method of measuring time was well enough suited to the slower pace of an agricultural life regulated by the sundial, it impeded the development of the mechanical clock.

In Japan our present system of twenty-four equal hours was not introduced until after 1870, and there is in the Science Museum a typical clock with a verge and foliot escapement made to overcome the problem of unequal or "temporal" hours. The clock has two foliots — one for day and one for night — on which the weights have to be adjusted every fifteen days. In Western Europe, Chaucer, who died in 1400, was still very much involved with "inequale houres". He mentions them in *The Knight's Tale*, and in his *Treatise on the Astrolabe* goes to great lengths in explaining how to convert the time as computed with the astrolabe into "inequale houres". Sir Thomas More, in *Utopia* (1516), feels obliged to demonstrate the need for "equal" hours by specifying that the Utopians use them. Shakespeare, however, nowhere mentions the question of unequal hours, since by his time all days in England were divided into twenty-four equal hours.

Running parallel with this early rationalization of time measurement is the ability of the writer to share with his audience the conception of increasingly small divisions of time. Chaucer nowhere mentions minutes (except in the astronomy of *Treatise on the Astrolabe*); Shakespeare uses the term more than sixty times, but he can come no closer to expressing a second than as "a jar [tick] of the clock" (*Winter's Tale* I.ii). Even minute hands were relatively unknown until the advent of the pendulum clock (1657), and right through the seventeenth century clocks were still being regulated by sundials.

Astronomy, however — through its handmaiden, horology — was beginning to change things. Whether or not Galileo actually saw the chandelier swinging in the Pisa of 1581 or 1582 and measured the isochronous timing against his pulse, astronomers for the next eighty years used pendulums maintained by hand for measuring the time of star transits. Galileo was also aware of the need to adapt the pendulum as an isochronous substitute for the inaccurate escapement of a foliot with verge and pallets. The verge and foliot escapement had controlled weight-driven clocks for some 300 years. Galileo (1564-1642) died before he could put his design into effect, and so did his son Vincenzo (d. 1649) who employed the artisan Domenico Balestri in an unsuccessful attempt to construct the clock.

Within less than twenty years, however, Huygens, another astronomer, had produced the first successful pendulum clock. Galileo's design involved a pin-wheel type of escapement that did not come into use until the following century. Huygens used the pendulum with the existing but inferior verge mechanism. The history of mechanical clocks is to a great extent the history of the improvement in their escapements. The escapement is the device which through a repetitive mechanical motion regulates the running down of the motive power. In 1657, Huygens (through the tradesman Salomon Coster) succeeded in substituting the pendulum for the foliot; he used the clock as a mechanical method for both maintaining the movement of the pendulum and counting the number of its relatively isochronous swings.

Like Galileo, Huygens was directly influenced by his need, as an astronomer, for accurate time measurement. He makes this clear in the *Horologium* (1659):

> Without doubt, accustomed to the faults in water-clocks and automata of various kinds used for observations, at last, from the original teaching of that most wise man, Galileo Galilei, the astronomers initiated this method: that they should impel manually a weight suspended by a light chain, by counting the individual vibrations of which just as many should be included as would correspond to an equal number of time-units. By this method they effected

observations of the eclipses more accurately than before; in like manner they measured — not unsuccessfully — the sun's diameter and the distances of the stars. But besides the necessary motion of the pendulum failing unless repeatedly assisted by the attendant, a further task was the counting of every oscillation; to this end, indeed, some kept vigil for whole nights with the most wonderful patience, as they themselves testify in their publications. . . .

After adding that he will describe how he has mechanized the use of the pendulum, Huygens says: "Astronomers certainly are adopting it [the pendulum clock], so that henceforth there will be no troublesome urging of pendulums nor watchful counting required."[5]

The question of using a mechanical timepiece at sea for determining the longitude was very much in Huygens' mind. At the beginning of the *Horologium*, he says: "the so called science of longitude, which, if ever it existed, and so had proved the greatly desired help to navigation, could have been obtained in no other way, as many agree with me, than by taking to sea the most exquisitely constructed timepieces free from all error. But this matter will occupy me or others later. . . ."[6] That this matter was in the minds of other scientists, too, may be concluded from the closing request in Newton's letter to Aston, as early as 18 May, 1669. Newton wished to learn from the Dutch "Whither Pendulum clocks doe any service in finding out ye longitude &c."[7] Sprat, in his *History of the Royal Society* published two years earlier, says with an optimism that the British Admiralty would not endorse for more than one hundred years: "There is only wanting the *Invention of Longitude*, which cannot now be far off."[8]

It soon became clear that chronometers, like watches, could not operate satisfactorily with pendulums. Today, with the wisdom of hindsight, we might well wonder why Newton should even bother to enquire about the use of pendulum clocks at sea. But practical watchmakers made the same error. For a period, they produced watches with pendulum escapements, blinded at first, no doubt, by the remarkable and unprecedented accuracy of the pendulum clock. Samuel Butler, in *Hudibras* III.i, makes fun of the phenomenon by comparing virtuosos, or scientists, hanging pendulums to watches with the hanging up of a poor wretch:

[5] Christiaan Huygens of Zulichem, *Horologium* (1658), trans. Ernest L. Edwardes, in *Antiquarian Horology*, 7 (December 1970), pp. 43-44.

[6] *Ibid.*, p. 44.

[7] Isaac Newton, *Correspondence*, ed. H. W. Turnbull (Cambridge: University Press, 1959), I, p. 11.

[8] Thomas Sprat, *The History of the Royal Society* (London: J. Martyn, 1667), p. 382.

And did not doubt to bring the Wretches,
To serve for *Pendulums to Watches:*
Which modern Vertuoso's say,
Incline to Hanging every way.

In 1678, when the third part of *Hudibras* was written, this temporary phenomenon was particularly topical. Caillard's article on "The History of the Pendulum Watch" says that "As a timekeeper, it was rendered obsolete by the discovery of the balance spring [c. 1675], and an interesting stage is reached where apparent 'pendulum' watches have, in fact, a concealed counterpoise and balance spring."[9]

Boyle, the father of chemistry, was an almost exact contemporary of Huygens, and was also keenly interested in horology. In Boyle's plea for the value of the newly developing co-operation between science and the "mechanical arts", he holds back for his climax the great advantage that watchmakers derived from the invention of the pendulum clock: "we daily see the shops of clockmakers and watchmakers more and more furnished with those useful instruments, pendulum-clocks, as they are now called, which but very few years ago, were brought into request by that most ingenious gentleman [Huygens], who discovered the new planet about Saturn."[10]

Because experience demonstrated that the pendulum clock would not serve as a chronometer, Huygens made his second successful invention of the spring balance (c. 1674-75). In doing this, he was trying to find a suitable escapement for chronometers in sea-going conditions. Essentially Huygens was now substituting the isochronous qualities of the spring for those of the pendulum. Much as he had done with the pendulum, Huygens adapted the new concept to existing technology. The balance wheel (without isochronous qualities) had long been an alternative to the foliot.[11]

The spring balance provided the potential for an accurate portable escapement and complemented the spring drive which had earlier — from perhaps the latter part of the fifteenth century — given portability to watches and clocks. Ward says, "the movement of the early German watches was made entirely of iron or steel, probably because their makers were originally locksmiths [rather than the blacksmiths who generally

[9] Bernard Caillard, "The History of the Pendulum Watch," *Antiquarian Horology*, 3 (March 1960), pp. 41-43.

[10] Robert Boyle, *Works* (London: W. Johnston and others, 1772), III, pp. 397-99.

[11] There has been a long controversy about Robert Hooke's claim to the invention of the spring balance.

made turret clocks], but brass was gradually introduced about 1560 and its use soon became general. A similar change from iron to brass took place with portable clocks."[12]

Until the advent of the fusee, the spring drive increased the inaccuracy of clocks. This is because the force transmitted to the gear train by an uncoiling spring diminishes progressively. The fusee — Huygens calls it "a pyramid" in the *Horologium* — is a spirally grooved cone-shaped pulley of varying diameter attached to the mainspring by a cord or chain. It provides an excellent method for equalizing the force of the mainspring. The fusee is still in use in chronometers, in part because, unlike other modern watches, they do not need to be thin in appearance.

Though the spring drive and the spring balance were essential landmarks in the development of an accurate chronometer for use at sea, much further experimentation and adjustment would be required in order to attain the desired accuracy and compensate for such variables as temperature and motion.

The results of Huygens' pendulum and spring-balance escapements were revolutionary, but the process was part of an evolution (albeit an exponentially progressive one) to which Western technology seems fatally attached. The first pendulum escapement improved the accuracy of clocks by a factor of about sixty — from an error of between five and fifteen minutes per day to within ten seconds per day. The highly erratic performance of watches was at first reduced by the spring balance to an error of perhaps two to three minutes per day. By 1761, Harrison's fourth and most famous chronometer erred by no more than fifteen seconds after a five-month journey to the West Indies and back. Today, we have clocks that are correct to within one second in 30,000 years.

The increasing accuracy of clocks is related to the rationalization of time itself. We have already noted the change from unequal to equal hours. After the inventions of Huygens, it became increasingly obvious that clocks could no longer be regulated by sundials. These were themselves subject to a seasonal variation of up to thirty-two minutes per day (related to the equation of time), which had barely been noticed until clocks themselves became more accurate. The result was the introduction of the mean rather than the solar day. By 1883, the railways — through the agency of the Canadian, Sanford Fleming — had required the further rationalization represented by international time zones. This obviated the proliferation of local times that had passed unnoticed in the slower travel

[12] F. A. B. Ward, *Time Measurement: Historical Review* (London: Science Museum, 1970), pp. 24-25.

of previous ages. In 1967, the demands of much more precise timekeepers — now, in part, related to interplanetary travel — has required the separation of time measurement itself from a relatively erratic solar system. As a result, the second has been re-defined in terms of the vibrations of the Caesium 133 atom.

It will have been noted that Britain has played virtually no part in our story until the time of Huygens, a Dutch Protestant who did some of his best work in France before being obliged to leave by conditions related to the Revocation of the Edict of Nantes. *Britten's Old Clocks and Watches* says that "No English watch is known of a date before 1580 and only a short time before this is there any record of an English watchmaker."[13] Yet, within eighty years, England had developed a capacity for creative imitation highly reminiscent of the United States in the nineteenth century and Japan in our own time. Dryden points to this quality in his last great work *The Preface to the Fables* (1700): "the genius of our countrymen in general, [is] rather to improve an invention than to invent themselves, as is evident not only in our poetry, but in many of our manufactures". The British were making Huygens' pendulum clocks in England within one year of their invention. By the time that Tompion, the father of English watchmaking, died, in 1713, he had produced what was for then the prodigious number of some 6,000 watches and 500 clocks. I call the period 1660-1760 the British horological revolution because it was the British who then took the world lead in precision engineering and all that derived from it.

The relationship between horology and modern civilization has frequently been noted, though more detailed research is warranted. Lewis Mumford states: "The clock, not the steam engine, is the key machine of the modern industrial age." Commander Waters puts the case for the importance of navigation: "It is time which makes modern civilization practicable. But it is the provision of accurate time in ships at sea which lies at the core of civilization for its wealth is largely dependent upon the safe and timely passage of ships at sea."[14]

Bruton makes an even more specific claim concerning the British Admiralty's prize of twenty thousand pounds offered in 1714 for the discovery of a method to ascertain the longitude at sea: "The act of 1714 caused the same kind of surge of scientific effort that space research does today, and was in many ways responsible for the Industrial Revolution

[13] Cecil Clutton, and the late G. H. Baillie and C. A. Ilbert, *Britten's Old Clocks and Watches and Their Makers*, 8th edn. (New York: E. P. Dutton, 1973), p. 43.

[14] Waters, "Time," p. 82.

that followed. The invention of the marine chronometer, for which it was directly responsible, resulted eventually in the domination of the world by the British Fleet, the expansion of trading, and the acquisition of the British Empire."[15] Bruton may be stating his case a little strongly — the Act of 1714 merely adds further impetus to an existing movement — but in essence he is very right.

The story of John Harrison's single-minded work to gain the Admiralty's prize began perhaps as early as 1726, and concludes with the last instalment tendered reluctantly by Parliament on 21 June 1773. The story will not be repeated here. It is well known to most people at least in its outline, and admirably recounted by Harrison's biographer Commander Gould. It is a story of irony, because as early as 1737 a longitude prize might have been claimed for the H1 had the concept of rate been understood (for example, if a clock is known to lose exactly two seconds a day its "rate" is perfect); it is a story of apparent stupidity, because the Admiralty seems not to have understood the H4's losing rate of 2.66 seconds per day despite Harrison's attempt to explain this; and it is a story of inexcusable insensitivity, because the Rev. Nevil Maskelyne — who supported a quite different method for ascertaining the longitude — should have recognized his conflict of interest and refused to judge the case.

Though it seems a little surprising now, Maskelyne's complicated method of using lunar distances to find the longitude was in fairly common use until the nineteenth century. Cook himself still employed the laborious and complicated method of "lunars" for his first voyage of 1768-71. However, by the second voyage of 1772-75, Cook sailed with K1 and found that it gave the best performance of four timekeepers tested for ascertaining longitude. He referred to it as "our trusted friend".[16] On the third voyage of 1776-79 — the one with which British Columbians are most concerned — Bligh sailed as navigator and Vancouver was a midshipman. Captains like Cook, Bligh and Vancouver recognized the value of the chronometer quickly enough, and it served them well. But at first navigators had to buy their own chronometers, and the Admiralty did not make a general issue until 1818.

Just as occurred with the earlier pendulum and spring balance escapements for clocks and watches, invention was not enough. In order to consolidate success, production was equally important. But on this occasion British watchmakers were exploiting ideas that had first been used success-

15 Eric Bruton, *Clocks and Watches* (Feltham: Hamlyn, 1968), p. 84.

16 Rex and Thea Rienits, *The Voyages of Captain Cook* (Feltham: Hamlyn, 1968), pp. 77-78.

fully by one of their own countrymen. Harrison's H3 — which has given us as a by-product the ubiquitous thermostat — took nineteen years to finish and adjust, but John Arnold (d. 1799) and Thomas Earnshaw (d. 1829) made about one thousand marine chronometers each. In doing so, they brought the price down radically below anything that their competitors could offer.

Two hundred years after Cook's visit to British Columbia, it is hard to realize how recently this land was *terra incognita* both to navigators and to their map-makers. That is why, as late as 1726, Swift, in *Gulliver's Travels*, is able to place Brobdingnag, the enormous land of the sixty-foot giants, in the approximate area now covered in part by British Columbia. In Lilliput, a tiny island southwest of Sumatra, Gulliver himself had been the giant. His large silver English watch seemed to the uninitiated Lilliputians to be "either some unknown animal or the god that he worships". But the area north of San Francisco was so little known that Swift could inhabit it not only with giants but with giants who understood "clockwork (which is in that country arrived to a very great perfection)".[17]

Needless to say, neither Gulliver's watch nor the clockwork of the Brobdingnagians was by any means sufficiently accurate to determine longitude. Swift, like many of his circle, ridiculed such a possibility as the fanciful conception of scientists. In a letter to Archbishop King of 1712, he suggests that the chances of success are "as improbable as the philosopher's stone, or perpetual motion". Even as late as 1726, in *Gulliver's Travels*, he again suggests that "the discovery of the longitude" is about as likely as that of "the perpetual motion, the universal medicine, and many other great inventions" of the scientists that he ridicules in the "Voyage to Laputa".[18]

Nevertheless, within fifty years, the chronometer — in the hands of such adventurous sea captains as Cook, and later Bligh and Vancouver — would have made it very difficult for Swift to have placed Brobdingnag in its present or, indeed, in any credible earthly location. That is one measure of what the chronometer has done for us.

[17] "Lilliput" Chapter 2; "Brobdingnag" Chapter 3.

[18] "Laputa" Chapter 10.