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THE CONTRIBUTION OF THE MECHANICAL CLOCK TO THE IMPROVEMENT OF NAVIGATION

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LATITUDE SAILING AND THE FIRST MECHANICAL CLOCKS AT SEA

The importance of time scale definition in modern navigation is well known (1). The problem of time keeping and determination has in fact played an important role in the development of navigation since man began sailing the oceans.

In 1420 the Portuguese began their exploration of the Atlantic and, for about one century, up to Magellan's circumnavigation of the globe (1519-1522), oceanic navigation was practically a Hispano-Portuguese monopoly. After the second half of the XVI century the discovery of new lands and navigational routes was dominated by the commercial necessities of two new seafaring countries: England and Holland.

This great expansion in oceanic navigation was in turn the cause of an important technological revolution in navigational methods and techniques which brought about the change from pre-astronomical navigation, which went from the Prehistoric period to the end of the Middle Ages, to so-called astronomical navigation. As is well-known, this consists of establishing the position of the ship on the basis of the determination of the astronomical coordinates: latitude and longitude. The first latitude observations on the high seas were probably carried out towards the end of the XV century (2). A new era in oceanic navigation began at that time based on the technique of latitude sailing.

This technique is based on an estimation of the angular distance travelled by the ship from north to south or vice-versa by means of the measurement of the angular height of the North Star and the Sun with the use of large astrolabes and sea-rings (3) and, later on, sextants. Having reached the latitude of the point of arrival or landfall, navigation continued by keeping this latitude fixed and sailing along it with the aid of azimuth compass and log.

In latitude sailing it was necessary to measure time intervals to establish the speed and the distance the ship had travelled. Only when extra-meridian measurements of the Sun's height were carried out was it necessary to know the exact moment in which this observation was made. The most common way of finding the time at sea during the day in the XVI century was based on the use of the universal ring dial. At the end of the same century it became possible to determine the time even at night with the use of the so-called "nocturnal".

The keeping of time otherwise was based on the use of sand-glasses, presumably invented in the Mediterranean area during the XII or XIII century and used for the measurement of time intervals and the corresponding distance on a portolan or sea-chart (4).

The appearance of the mechanical clock towards the end of the XIII century was the expression of the important technological revolution going on at that time. This is not the place for a discussion of the invention of the mechanical clock and its escapement mechanism, known as the verge-and foliot, the origin of which is not completely clear, (5), but it must be said that in the XV century the mechanical clock was widely used for time-keeping on land in a whole series of activities. Among the reasons which kept mechanical clocks from being used in navigation, there was certainly the difficulty of finding an adequate technical solution to the problem of the clock's suspension so as to avoid malfunctioning or stoppage because of rough seas.

The possibility of researching the role played by the mechanical clock in sailing at this time and for the improvement of navigation is made quite difficult by the lack of reliable documents. If, as seems to be the case, English ships did not use mechanical clocks on board until the XVII century, it is certain that on Dutch ships these were used starting from the end of the XVI century. The use of new time-keeping technologies by the Dutch is not surprising if it is kept in mind that from the middle of the XVI century and for the next hundred years they monopolized oceanic navigation and the search for new commercial routes.

The only document we have on the use of the mechanical clock at sea concerns its use by Willem Barentsz, a whaler and well-known explorer, during the expedition which began in 1596 in the search for the North-East passage and now conserved in the Rijksmuseum of Amsterdam (6).

The use of the mechanical clock with the balance wheel at sea was dependent on its intrinsic precision and the use to which it was put.

Regarding precision, the kind of clock with an hour hand used by Barentsz could cause an error of about 5 to 10 minutes per day. Precision was greatly improved in the second half of the XVII century with the introduction of the dial-plate indicating the minutes. Up to this time it is probable that the mechanical clock was used exclusively as standard shipboard time-keeper beside the sand-glass. The importance of the use of the mechanical clock as a time-keeper at sea was greatly accentuated by the introduction of methods of astronomical longitude determination.

THE FINDING OF LONGITUDE AT SEA BY ASTRONOMICAL METHODS

As has been seen, during the XVI century longitude was still estimated by dead reckoning, a most inaccurate method because of uncertainty in measurements caused by breezes, tides and currents. As Nevil Maskelyne wrote in the preface to his *British Mariner's Guide* in 1763 referring to this method: "Five, ten or even fifteen degrees are errors which no one can be sure he may not fall into in the course of a long voyage".

Only after the use of the telescope in 1609 by Galileo (1564-1642) were some astronomical methods proposed and used for longitude determination. As longitude can be found only by measuring the difference at the same moment between the local time of the ship and the local time of longitude zero or prime meridians, it was thought that the observation of celestial phenomena visible over a large part of the Earth's surface could resolve the problem.

The practical method proposed by Galileo was based on the observation of the eclipses of Jupiter's satellites, which he had discovered in January 1610. This method, as Galileo himself stated, required, "first of all a precise knowledge of the movements of Jupiter's satellites and the definition and distribution of the ephemerides of the instants of the eclipses in the time of the first meridian. Secondly the building and use of telescopes of such perfection as to make clearly visible and observable the phenomena of the eclipses. Thirdly the discovery of artifices capable of overcoming the problems deriving from the ship's movement while using the telescope. And finally the realization of a very precise clock to number the hours and the fractions of the hours." (7). As can be seen, Galileo's project was an attempt to find an overall solution to longitude determination at sea. To make these proposals operative in fact, he suggested solutions he felt were practicable (8). In particular, as regards the "measurer of time", based on the oscillations of a pendulum of his invention accurately described in the letter to Lorenzo Reaglio dated 15 June 1637 and in other letters and publications (9), it is a pity Galileo was not able to realize his "misuratore del tempo" for longitude determination at sea. Galileo attributed unusual precision to this "time-measurer", more than one order of magnitude greater than common mechanical clocks of the epoch (10). A kind of manual for the construction and use of such a "time-measurer" was published in Paris in 1639, probably by Mersenne, under the title: *L'usage du cadran de l'horloge physique universelle* par Galilée, Mathematicien du Duc de Florence.

As is known, Galileo's proposals for solving the problem of longitude determination by observation of the eclipses of Jupiter's satellites, made first to the King of Spain and later to the Netherlands, met with no success for various reasons (11), and only from about 1690 were Galileo's methods for finding the longitude used rather extensively, but only on land. Thus, his proposal for the realization of a "time-measurer" with a pendulum for the determination of longitude at sea remained on the drawing board.

In 1514, Johann Werner (1486-1522), in his edition of Ptolemy's *Geography* (12) had suggested another astronomical method for the finding of longitude based on the measurement of the distance between the moon and the fixed stars, including the sun (13). This method involved measuring the angular distance between the moon and the sun or stars with a cross-staff and successively a reflecting quadrant and sextant, and predicting, by calculation, the times, in relation to the prime meridian, when the moon would be at the angular distance from the star as seen from the ship.

Amerigo Vespucci had already observed that "the lighter course of the moon" among the stars could be used in longitude determination at sea (14). However, the difficulty of knowing the moon's position in advance with great accuracy and the complexity of the reduction calculations contributed to its use being discouraged in navigation, at least until the beginning of the XVIII century. This explains the failure of attempts made in the early part of the XVII century (1637) by John Baptist Morin (1603-1656), when he proposed to the King of France the preparation of lunar tables corrected for refraction and horizontal parallax in view of making lunar observation available for the determination of longitude at sea.

The only navigator at the beginning of the XVII century who used a method based on the moon's motion for longitude determination at sea appears to be William Baffin (1584-1622) during his voyage to Greenland (15). The difficulty in using methods based on lunar motion derives not only from the inaccuracy of lunar tables, but also from the inadequacy of the mechanical clocks and sand-glasses used on board for time-keeping during the day. The situation induced most investigators to consider the possibility of providing a more correct timekeeper.

It is interesting to observe that together with the various attempts to better the performance of the clocks used in longitude determination, a great effort was made to improve knowledge of lunar motion in order to solve the longitude problem at sea. These efforts led to positive results thanks to the fact that three events of revolutionary importance took place simultaneously in the second half of the XVII century:

i) first of all the creation of scientific organizations such as the Royal Society (1662) and the Académie des Sciences (1666) and of institutions for astronomical research such as the astronomical observatories of Paris (1667) and Greenwich (1675) which created the operative bases for tackling the problem of longitude determination at sea. The Royal Observatory at Greenwich had been founded with a clear mandate to rectify "the table of the motions of the heavens, and the places of the fixed stars, so as to find out the so much desired longitude of places for the perfecting of the art of navigation";

ii) secondly, thanks to the contribution of a great number of astronomers, mathematicians and physicists the grounds were laid for the research, which culminated with the publication of Newton's *Principia*, leading to the discovery of the physical laws of motion, whose application to the motion of the heavenly bodies and clockwork movement allowed the solution of a whole series of theoretical and practical problems. It must not be forgotten that "the investigation of timekeepers for the longitude was subordinate to an even larger project launched and carried forward by the same group of men, that of constructing a theory of the laws of motion and establishing the Copernican theory upon a sure foundation of mechanics" (16);

iii) finally, the foundations were laid for that important technological revolution which, with the definition of new technological capacities and competence and the emergence of a new professional class of technicians in the field of optics, mechanics and chronometry, led to the realization of new and more precise instruments for the measurement of time and angles, with the application of the telescope to the graduated instruments.

Here it can only be mentioned in passing that John Falmsteed, the first Astronomer Royal, and his successors, not only were convinced of the impractability of finding the longitude by any method but that derived from a perfect knowledge of the moon's motion, but also worked on the problem of the moon's motion, with the purpose of improving the accuracy required for a satisfactory lunar theory (17). It was not by accident that the ships of the East India Company were equipped regularly with marine clocks only from about 1770 onwards (18).

THE ROLE OF THE MECHANICAL CLOCK IN LONGITUDE DETERMINATION AT SEA

Experimentation with the pendulum as a timekeeper began in England, Holland and Italy at about the same time, stimulated by Riccioli's recommendation of its application in his *Almagestum* of 1651 (19), and greatly influenced by Galileo's proposals as well as Mersenne's study on pendulum isochronism (20). However, we do not know if the first attempts following this to apply the pendulum to mechanical clocks, both weighted and with springs, for longitude determination at sea, were made in the hopes of constructing timekeepers to be used for keeping time day by day, that is, as a means of measuring longitude by lunar distance, or if the intention was that of realizing actual marine clocks to be used for the keeping of the time zero meridian on deep-sea ships during long voyages.

The idea of determining longitude differences by transporting timepieces goes back, as is known, to Gemma Frisius, who expounded it in 1530 in his book *De Principis Astronomiae et Cosmographiae* (22), even though in 1510 Alonso de Santa Cruz had proposed the same method for longitude determination at sea (23). The invention of the fusée, about 1525, certainly contributed to nourishing the belief that the new improved portable timepieces would be capable of giving more or less uniform time during twenty-four hours also at sea.

The fact remains that until halfway through the XVII century no real change was introduced into the methods of astronomical navigation for the determination of longitude.

It is possible, starting from this period, to single out three distinct phases in the development of a mechanical clock intended for marine use. In the first phase, which began about 1660 and finished in the period from 1675 to 1680, it is difficult to establish from the technical point of view just what differences there were between normal pendulum clocks and those explicitly designed for longitude determination at sea.

From the description of the first pendulum clocks in the *Horologium* constructed by Samuel Coster starting from 1657, it is evident that the goal of Huygens was that of realizing a precise timekeeper for astronomical purposes rather than for longitude determination, even though in manuscript K, written between 1656 and 1657 (24), Huygens quotes the *Geography* of Metius with reference to the longitude problem. This fact brought about an objective delay in the realization of marine clocks capable of competing with longitude determination techniques based on the measurement of lunar distances. In effect, only from 1661-62 can we date the adaptation of two of Huygen's clocks by Alexander Bruce for the precise purpose of determining longitude at sea (25). The story of these two clocks is reported in detail by Drummond Robertson (26). It is interesting to observe that these two clocks, driven by a spring like Coster's first clocks, differ from these and from the clock described in *Horologium* in 1658 because of the different suspension of the pendulum between the cycloidal cheeks, with its rod held between two jaws in a special crutch in order to prevent a rotary motion of the pendulum at sea. The performance of these clocks at sea, tested during a voyage to London undertaken by Bruce himself in 1662, and later during a voyage to Lisbon in 1663 in the charge of Captain, later Admiral Robert Holmes, was not completely satisfactory (27).

Better results seem to have been given by these clocks during the tests they underwent during the voyages between Africa and America by Captain Holmes in 1665-66 (28). Relative variations even of several minutes (3 to 7) were noted at the end of the voyages (29). Daily delays on the order of one minute were reported by de la Voye in longitude determinations at sea between Toulon and Crete (30). These alternating results influenced the opinion of Huygens himself as regards the possibility of using mechanical pendulum clocks in longitude determination at sea. So, in November 1663, he wrote to Moray that "clocks will never give longitude with the greatest perfection even though they will always be of great help as their use is perfected", while in February 1664, after having designed his "remontoire" device, licensed in Holland in December 1664, he wrote something quite different in his letter to Johan de Witt (31). Scepticism on the possibility of the use of mechanical clocks in the period from 1670 to 1675 was also clearly expressed by Giovanni Hevelius. In his *Machina Coelestis* (1673) he wrote: "Some nourished the hope of finally discovering the distances from the meridians and the exact longitude of places with the help of these pendulum clocks: with this system the calculation never comes out, in my opinion, according to what is expected, especially on these very long voyages lasting several months" (32).

The fact remains that even after his moving to Paris in 1666 and experiments on Dutch and French ships the performance of the clocks of Huygens, still of the type tested by Bruce, showed no improvement. On the voyage from Toulon to Crete in 1669 an error of about two degrees, corresponding to about eight minutes in time, was noted (33).

The history of the marine clock proposed by Bruce and Huygens is quite interesting and is closely connected with that of clocks designed for the solution of the longitude problem in England and Italy in the same period.

The recent history of chronometry has pointed up the fact that the period from 1656 to 1660 was crucial in the development of the mechanical clock and, in this period, perhaps even before Coster's clocks, in Switzerland, Germany, France and Italy pendulum clocks with special characteristics, like the clocks with the escapement at the bottom and the horizontal crown-wheel downwards, built in Rome and Florence (34), were being designed and produced.

In the same way we are of the opinion that in the following period that idea of producing marine clocks was cultivated and realized, independently, even outside Holland. Already in 1660 Giuseppe Campani, in his *Discorso intorno ai suoi muti oriuoli*, declared that he had invented a clock of great precision, and much more perfect than the pendulum regulator, for determining longitude at sea. He did not discuss this new type of clock, but it is known that for several years he carried out experiments on this project (35). Some years later, in 1662, Giuseppe's elder brother Matteo published his *Nuova invenzione d'oriuoli giustissimi ad uso della navigazione*, reprinted the next year (36), in which for the first time we have the presentation of a pendulum clock inside a glass bell to protect it from the effects of atmospheric pressure and supplied with a double compensatory system for the neutralization of the ship's pitching and rolling (37). In the period from 1658 to 1660 in England Robert Hooke carried out his abortive project for patenting and marketing watches. Although in this country the first investigations of timekeepers for longitude determination was subordinate, "to an even larger project, that of constructing a general theory of the laws of motion" (38), there is no doubt that these activities were the basis for the later practical contributions made by Bruce and Hooke to the realization of marine clocks.

THE BIRTH OF THE MARINE TIMEKEEPER

Until about 1675, the results of the use of mechanical clocks by Bruce and Huygens in navigation were discouraging. No change took place in this situation, as has been seen, even afer the introduction of weight-driven clocks with a nine-inch pendulum devised by Huygens and employed during the expedition in 1669 to expel the Turks from Crete (39).

Things did not change after the uncertain use at sea of the new clock without the little chain, the so-called clock à remontoire, built by Thuret in Paris from 1665 onwards (40), and of the triangular pendulum clock driven by a spring, designed in the period from 1671 to 1672 (41) but used at sea only during the two voyages to the Cape of Good Hope by Thomas Helder and Jo. de Graef in 1686-87 and and 1690-92 (42). On this latter voyage the difference in longitude between the Cape and Santiago calculated with the clocks on board was incorrect by more than six degrees (43). We do not know if the discovery by Huygens of the general conditions for isochronism of the springs after the publication of the *Horologium oscillatorium* in 1673 is bound up with the idea of improving the performance of the marine clocks.

Robert Hooke had already discovered that the spring was a "tautochrone" before 1666 and made the first application of a spring to a marine timekeeper in 1675 (44), the same year in which Huygens made his discovery known (45,46). It is probable that the spiral spring balance was applied to some marine clocks sometime about 1683 (47), and in any case not before 1679, to judge from a letter by Huygens to Paul Pellisson in which he states that "the last trials with pendulum clocks at sea have not been wholly unsuccessful, but, as they necessarily suffer from the motion of a vessel, there is more hope of success with balance with a spiral spring, etc."(48).

Nevertheless the adding of a spiral spring to the oscillating balance wheel in 1675 by Huygens did not yield the results that he expected, principally on account of the influence of temperature (49).

The unreliability of the first spiral spring timekeepers and the low esteem displayed by Huygens for this kind of clock, demonstrated by the fact that he himself discarded the idea first put forward in 1665 by Hooke on the possibility of applying a spring regulator (50), inspired Huygens to re-examine new types of marine pendulum clocks. The project of the "pendulum cylindricum trichordon" (51), whose torsional oscillations were shown by Huygens to be almost isochrone, bears the date 1683. But the realization of isochronous marine clocks based on this principle proved to be most uncertain even though it seems that two of these clocks were built by the famous Dutch clockmaker Johannes Van Ceulen (52). In 1683, however, Huygens, writing to Fullerius states that "at the request of the (East Indies) Company, he had undertaken the construction of clocks to determine the longitude, possessing as constant a regularity as those with the three-foot pendulum, but such as should not be disturbed by the motion of the sea" (53).

From 1675-80 to 1710-15, a second phase in the development of marine clocks can be singled out. This is a stage of meditation on the precarious state of marine timekeeper technology following the previous phase characterized by a certain optimism.

It is a phase particularly poor in results and innovations in marine clocks but one in which the great, decisive steps in the application of chronometry to astronomical navigation that will take place in the first half of the XVIII century are being prepared. In this period we have the projects Huygens elaborated from 1693 onwards but already singled out ten years before (54), for the realization of a "balancier marine parfait" (55) together with other devices for improving the accuracy of marine clocks (56). In particular, Huygens' attention is focused on the problem of the train friction and the equilibrium of the balance wheel, on which his successors will concentrate their efforts.

These successors did not overlook the fundamental importance of the escapement in improving the performance of timekeepers. They used escapements different from the traditional crown-wheel escapement always used by Huygens, such as the anchor escapement invented by Hooke and introduced by William Clement about 1680, or the "dead-beat" escapement devised by George Graham about 1719-20.

About 1715, the time was ripe for the final phase in the realization of a marine clock capable of resolving the problem of longitude determination at sea. At the end of this third phase it was decided to abandon once and for all the lunar distances method for the finding of longitude at sea, which had been upheld by the Greenwich astronomers in particular. But this did not take place overnight. Only about 1770, when marine clocks reached an accuracy of just a few seconds a day and surpassed by one order of magnitude the accuracy of the timekeepers supplied to navigators at the beginning of the XVIII century was it decided to abandon the old methods of longitude determination at sea and the Companies regularly equipped their vessels with the new chronometers. This took place between 1770 and 1790 (57).

The conditions that guaranteed this true revolution were the development of technology in France and England in the first half of the XVIII century and economical incentive. This latter condition was initially favored by the "Act for providing public reward for such person or persons as shall discover the longitude at sea", passed by the British Parliament in 1714 on the recommendation of a commission, of which Isaac Newton was a member. The award was fixed at 10,000, 15,000 and 20,000 pounds sterling.

The protagonists of this technological and horological revolution were Henry Sully, James Harrison, Ferdinand Berthoud and Pierre le Roy. With them it can be said that the modern marine chronometer was born and a significant step forward made in the improvement of astronomical navigation.

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