HOW TO MEASURE LONGITUDE

BY ANDREW ROBINSON

Before we were able to plot our position at sea, thousands of sailors lost their lives; the genius of one British clock-maker changed all that and won the prestigious Longitude Prize in the process

DESPITE THE PATRIOTIC claim in '*Rule, Britannia!*', the anthem composed in 1740, Britain was actually far from 'ruling the waves' in the mid-18th Century. As the Royal Navy was only too painfully aware, neither British sailors nor the seamen of any rival nation, such as France or Spain, had a reliable way to determine their position in the open ocean. This was especially true during foul weather, when it was impossible to observe the positions of the Sun, Moon and stars. Navigation and landfall remained always a precarious affair.

In 1741, a British naval squadron lost its way – along with several ships and more than half of its crew – off the western tip of South America because its estimate of its longitude was some 200 miles in error. Much closer to home, in 1707 a British fleet returning from France became lost in fog near the western end of the English Channel. Its commander, misjudging his position as west of the island of Ushant (at the furthest tip of the Brittany peninsula), sailed north and ran his warships into the rocks of the Scilly Isles, which are located a whole degree of longitude west of Ushant. Four ships were smashed and 1,647 sailors drowned; only 26 survived.

As a result of the 1707 catastrophe, the British Parliament passed the Longitude Act in 1714. This stipulated enormous cash prizes for anyone – British or otherwise – who could invent a method of measuring longitude that would be effective at sea. The top prize, £20,000, was offered for a method accurate to half a degree of longitude. Furthermore, the act established a Board of Longitude to adjudicate the validity and practicality of proposed methods, which consisted of scientists, naval officers and government officials. They included the president of the Royal Society (Sir Isaac Newton), the first lord of the Admiralty, the speaker of the House of Commons, the first commissioner of the Navy and professors of mathematics at Oxford and Cambridge. Imaginatively, Parliament also empowered the committee to offer financial grants to develop promising proposals.

Hipparchus came up with a framework of lines of latitude and longitude on the celestial sphere

GREEK GENIUS

The concept of longitude, and of course latitude, dates back to ancient Greek mathematicians and astronomers who accepted that Earth was essentially a sphere. Earth's circumference was measured with considerable accuracy by Eratosthenes in the third century BC, but without specifying any terrestrial lines of latitude and longitude. These were invented in the 2nd Century BC by Hipparchus, who also compiled the first known star catalogue, with about 850 stars measured in terms of celestial latitude and longitude. Hipparchus's framework strongly influenced

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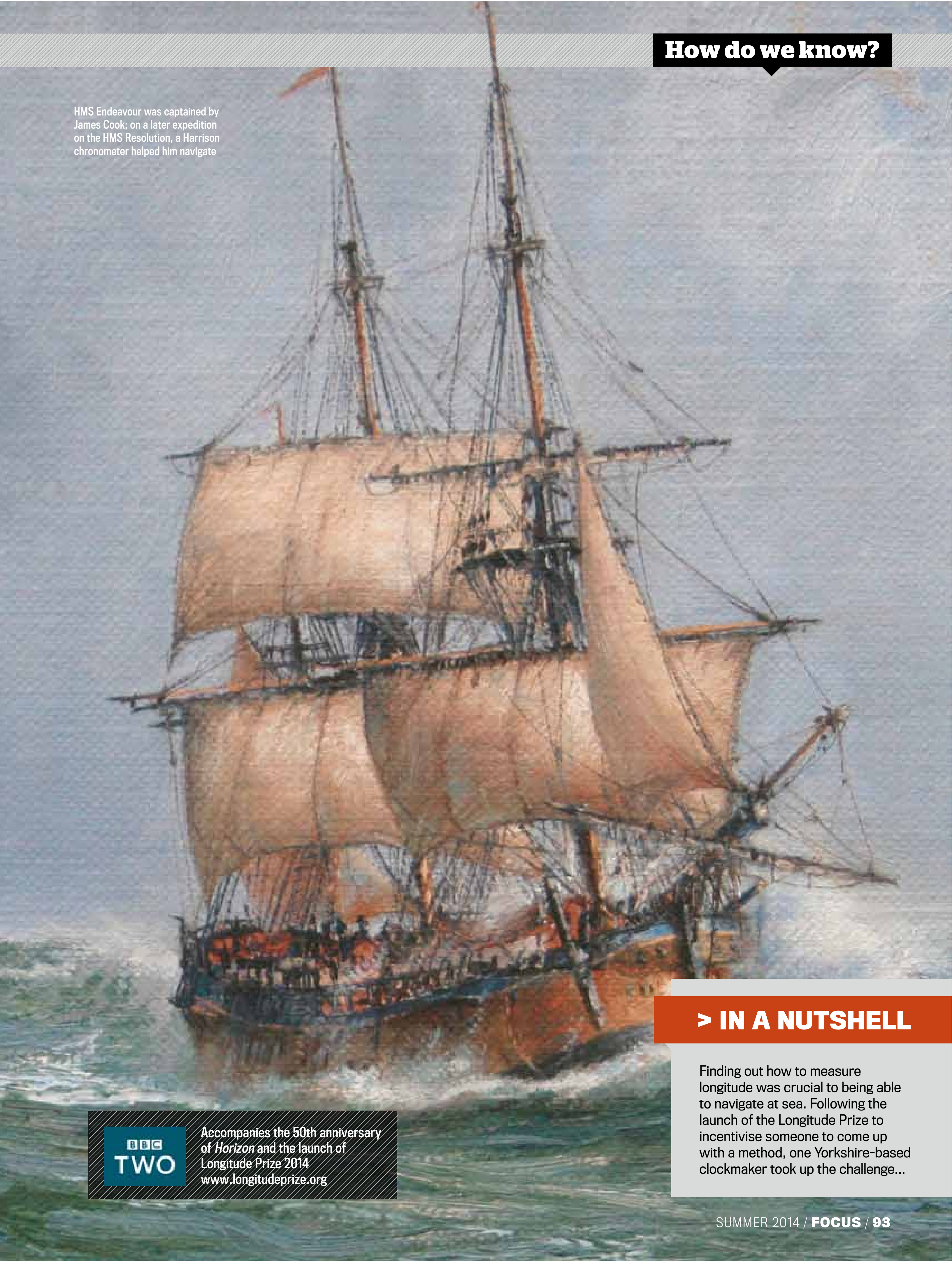


HMS Endeavour was captained by James Cook; on a later expedition on the HMS Resolution, a Harrison chronometer helped him navigate

> IN A NUTSHELL

Finding out how to measure longitude was crucial to being able to navigate at sea. Following the launch of the Longitude Prize to incentivise someone to come up with a method, one Yorkshire-based clockmaker took up the challenge...

BBC TWO

Accompanies the 50th anniversary of *Horizon* and the launch of Longitude Prize 2014 www.longitudeprize.org

Ptolemy, the father figure of cartography, in the second century AD. Ptolemy measured his terrestrial longitudes in degrees eastwards from a prime meridian running through the Fortunate Isles (Canaries), and his latitudes in degrees north and south of the equator.

To determine the longitudes of places on his map of the known world, Ptolemy used Pythagoras's theorem of right-angled triangles to calculate the difference in longitude between places A and B. The trouble was that the two 'known' sides of each of Ptolemy's triangles were the distance along a parallel of latitude between the latitudes of A and B, and the actual distance between A and B as the crow flies (the hypotenuse of the triangle). Both were imprecise, because of uncertainty about the size and shape of the Earth. Even assuming the Earth to be a perfect sphere, no one knew its exact circumference, or the length of a degree of latitude or longitude on the ground.

A possible method for measuring longitude, understood by the ancient Greeks, involved the equation of longitude with time. As the Earth rotates on its axis, the time of sunrise gets later the further west you are from a given longitude. For this reason, New York time is today set five hours behind Greenwich time in London, San Francisco time three hours behind New York, and Honolulu time two hours behind San Francisco. The 360 degrees of longitude are encompassed during the 24 hours of the Earth's complete rotation, which means that for every one-degree change in longitude the local time changes by four minutes. Thus the local time on the opposite side of the globe (180 degrees different in longitude) differs by 4 x 180 = 720 minutes, or 12 hours, as we should expect. If navigators were to compare their local time, as measured from the celestial clock by detailed astronomical observations, with the time measured in London at the time of their observations, they would be able to compute their longitude.

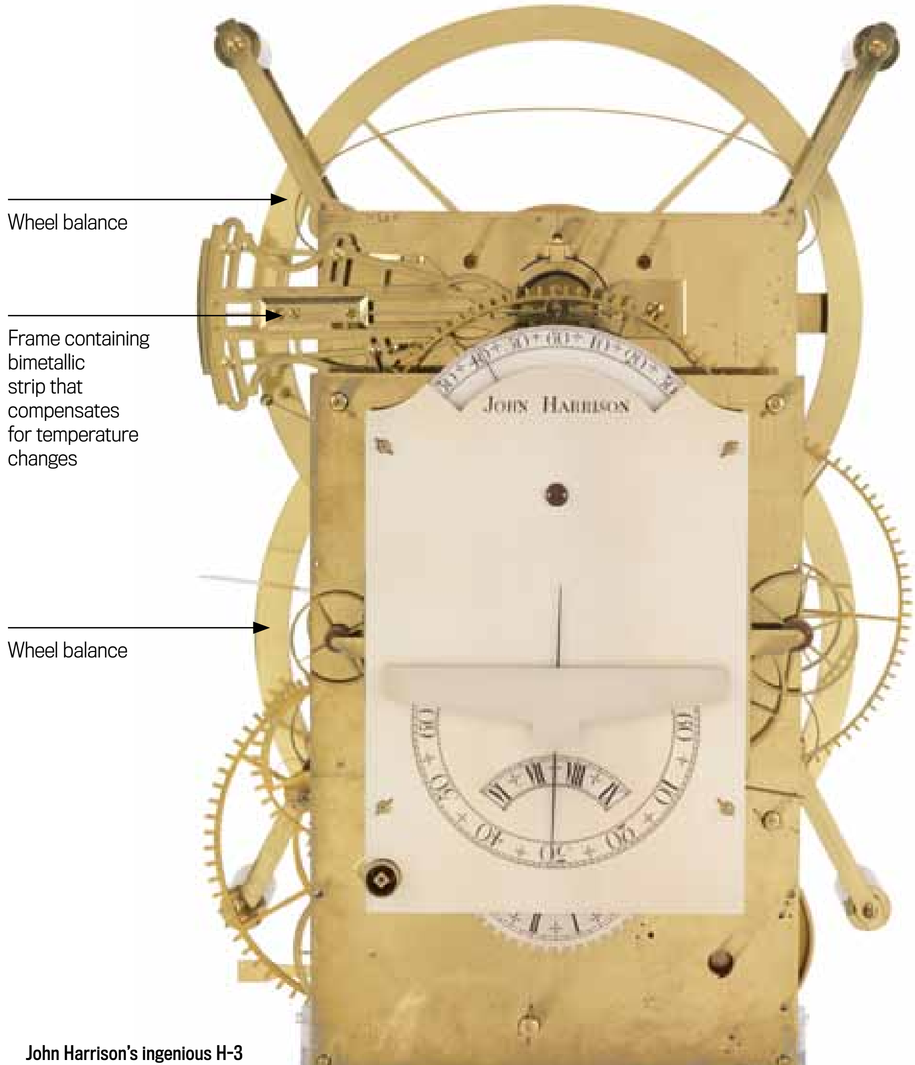
THE KEY DISCOVERY

John Harrison invented an ingenious device for compensating for the effects of temperature in a chronometer. It enabled longitude to be deduced from time

TEMPERATURE VARIATIONS reduce a mechanical clock's accuracy through thermal contraction and expansion of its pendulum or balance spring. John Harrison produced an initial solution to this problem in the 1720s, while making grandfather clocks. His pendulum comprised rods of steel and brass (which differ in their coefficients of expansion) parallel to each other but of differing length. They were connected in a so-called 'gridiron', such that the pendulum remained the same length no matter its temperature.

Cleverer still was Harrison's invention in his H-3 chronometer (pictured), some time before 1749, of the 'bimetallic strip' – a device nowadays familiar from mechanical central-heating thermostats. He riveted together a thin steel strip and a thin brass strip of the same length. When the temperature increased, the brass expanded more than the steel and curved the strip in one direction. When the temperature fell, the brass contracted more than the steel and curved the strip in the opposite direction. Two small 'curb pins', attached to the free end of the bimetallic strip and embracing the outer turn of the balance spring, reduced the spring's length slightly with temperature rise, or increased it with temperature fall, compensating for its thermal expansion or contraction.

Harrison's H-3 timekeeper



John Harrison's ingenious H-3 chronometer, which was the first to introduce the bimetallic strip

The method appears very neat but, when it was proposed by astronomer Gemma Frisius in 1530, it suffered from a fatal flaw. At this time, no suitable clocks of remotely sufficient accuracy existed. During the 17th Century, the measurement of time improved with the invention of the pendulum-regulated clock by Christiaan Huygens in 1656, followed by his patenting of the spiral balance spring in 1675 – an idea that had earlier occurred to Robert Hooke – which was soon incorporated into clocks. But sea trials of a pendulum clock built for Huygens in the 1660s showed it to be unreliable when a ship swayed, while Hooke's balance-spring clock was never tested at sea. Moreover, both designs suffered from the effects of temperature variation, which caused pendulums and springs to expand with an increase in temperature, and vice versa.

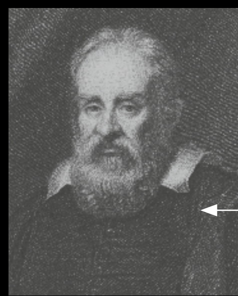
JUPITER TIMEPIECE

A second possible method for measuring longitude was entirely astronomical, employing careful observation of heavenly bodies. In Italy, Galileo Galilei, pioneer of the refracting telescope, made an exciting proposal in 1612. For a year Galileo had recorded through his telescope the movements of Jupiter's moons and concluded that the moons' eclipses by the planet occurred so frequently and predictably they could be used anywhere in the world as a celestial watch to calculate time, and hence longitude. But although Galileo's idea was sound, to apply it was feasible only on land (where it was widely used after 1650), not on deck; and it was useless during daytime when Jupiter was invisible, or indeed at night if the sky happened to be overcast.

Astronomical measurers of longitude were therefore forced to rely on the so-called method of 'lunar distances'. Unlike Jupiter's moons, Earth's Moon changes position clearly and substantially. In theory, this allowed navigators to compare their locally measured altitude of the Moon above the horizon, the altitude of a certain star above the horizon and the angular distance between the Moon and the Sun with printed tables. These showed the same configurations made in London or Paris at particular times of the day and night on the same date. Since the navigator knew his local time from the heavens, he

CAST OF CHARACTERS

Figuring out how to measure position on the planet has taken centuries of scientific endeavour



Galileo Galilei (1564-1642), a founder of modern science, was a pioneer of the refracting telescope. In 1610, he squinted through it at Jupiter's four moons, and began to record tables showing the times of their appearance and disappearance around Jupiter. Galileo suggested his tables be used by navigators as a celestial time check to calculate their longitude.

Christiaan Huygens (1629-95), a Dutch physicist, mathematician and astronomer with many achievements, he is perhaps best known for his invention of the pendulum-regulated clock in 1656. He believed it suitable for determining longitude at sea. Atlantic trials were initially encouraging, but soon it was clear that pendulums only worked properly under conditions of flat calm.

John Harrison (1693-1776) was an English carpenter-turned-clockmaker. Inspired by the prize money offered in the 1714 Longitude Act, he completed his first marine chronometer, now known as H-1, in 1735, and his last, H-5, in 1770. Though actively supported by the Royal Society, his work aroused keen opposition from astronomers. Harrison triumphed only in 1773.

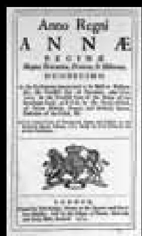
James Cook (1728-79), the great explorer, made his first Pacific voyage in 1768-71, when he was not permitted to take John Harrison's unique chronometer, H-4. He took a copy on his second and third voyages, which proved invaluable for navigation and cartography. It supposedly stopped ticking at almost the moment of Cook's murder in Hawaii.

Nevil Maskelyne (1732-1811), an Astronomer Royal, was convinced that longitude was best measured at sea by astronomical observation, not by a chronometer. He therefore undermined Harrison's marine chronometer in the 1760s. Using astronomy, Maskelyne launched the Nautical Almanac in 1767, which established Greenwich as the prime meridian of longitude.

TIMELINE

Figuring out how to find Longitude enabled us to explore and map the planet

1714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The Longitude Act, passed by British Parliament under pressure from merchants and mariners, offers cash prizes for any 'Person or Persons as shall Discover a proper Method for finding the Longitude'.

1761-62

John Harrison's No. 4 marine chronometer is trialled on a sea journey between Britain and Jamaica. In two months it loses five seconds, corresponding to an error in longitude of just two-hundredths of a degree.

1772-75

Captain James Cook takes a copy of Harrison's No. 4 chronometer on his second voyage of discovery. With occasional astronomical corrections, it enables Cook to make remarkably accurate charts of the Pacific.

1884

The prime meridian of longitude is established in Greenwich at an international conference, as a consequence of sailors long calculating their position from astronomical tables in the Nautical Almanac, compiled in Greenwich.

1978

The Global Positioning System (GPS) begins, with the launch of its first space satellite. Four satellites are required to fix the latitude and longitude of a point on the Earth's surface with an accuracy of a few millimetres.

PHOTO: NATIONAL MARITIME MUSEUM/MINISTRY OF DEFENCE ART COLLECTION X2, SCIENCE PHOTO LIBRARY X2, US NAVY

could in principle figure his time difference with London or Paris, and hence his longitude. However, the 'lunar distance' calculation was fairly difficult, requiring correction for the effects of refraction, parallax and the dip of the horizon. An imperfection in the observer's telescope, a substantial error in the lunar tables (very likely, noted Newton), or the inevitable rolling of the ship and the probable lack of training of the observer, would each be enough to make nonsense of the observation.

TIME FOR CHANGE

As the 18th Century progressed, however, increasingly good telescopes became available. At the same time, the accuracy of lunar tables improved – most notably in the Nautical Almanac, published from the Royal Greenwich Observatory from 1767 under the aegis of the Astronomer Royal, Nevil Maskelyne. Indeed, it was these tables that would eventually earn Greenwich its position as the prime meridian of longitude at an international conference in 1884. Most scientists therefore favoured astronomy, rather than chronometry, as the best long-term bet for measuring longitude at sea.

But in the same period, the accuracy of time-keepers dramatically improved, too – thanks to the skills of a carpenter-turned-clockmaker John Harrison. Born in modest circumstances in Yorkshire in 1693, he somehow got to hear of the Government's prize for finding longitude. His first timepiece, built in 1715, was a grandfather clock similar in almost every respect to others of its day. However, he soon turned to making more original and elaborate mechanisms. In particular, he confronted the problems of temperature, by creating a pendulum whose length remained the same regardless of temperature changes. By 1726, he had completed a clock that varied by no more than a second a month over the next 14 years. This brought Harrison to the attention of the Astronomer Royal, Edmund Halley, and Britain's leading horologist, George Graham. Graham personally advanced him money, without interest or security, to build his No. 1 chronometer, known as H-1.

Completed in 1735, using a balance spring rather than a pendulum, H-1 was sent on a sea trial to Lisbon. On its

NEED TO KNOW

What exactly are longitude and latitude? Find out below

1 LATITUDE

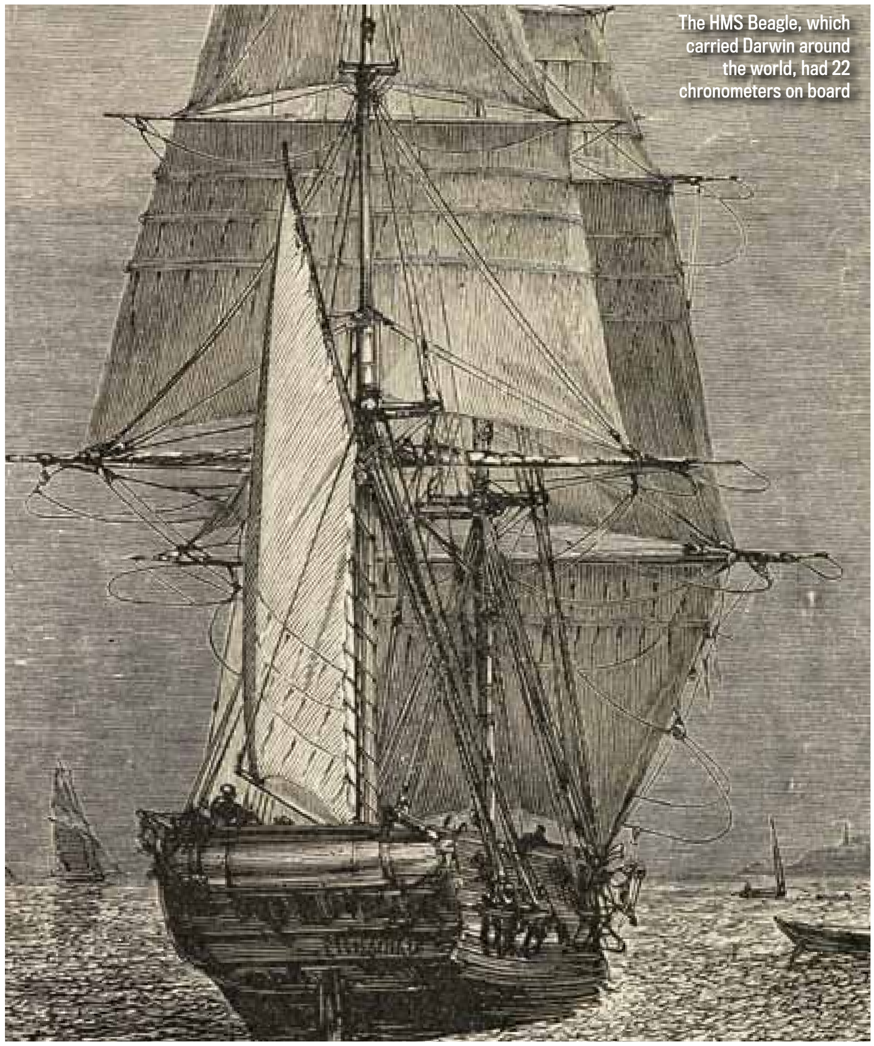
The Earth's equator is the parallel of zero latitude. The North Pole is at latitude 90° North, the South Pole at latitude 90° South. The parallels encircling the Earth between these extremes, expressed in degrees and minutes, are defined as the angular distance on a meridian north or south of the equator.

2 LONGITUDE

In contrast with latitude, longitude is defined not by Nature but by human choice. The prime meridian, encircling the Earth through the poles, happens to run through Greenwich, having been selected at a conference in 1884. All other meridians define the angular distance east or west of the prime meridian.

3 TIME ZONES

The establishment of Greenwich Mean Time (GMT) in 1884 created official international time zones and the international date line through the Pacific Ocean. This lies at 180° of longitude from the prime meridian at Greenwich.



The HMS Beagle, which carried Darwin around the world, had 22 chronometers on board

return, the chronometer corrected the landfall in Britain by nearly 100 miles. It gained Harrison the financial support of the Royal Society and the Board of Longitude in making four more chronometers over the coming decades. H-3, completed in 1757, was never sent to sea, but it contained Harrison's most important innovation: a 'bimetallic strip'. This allowed for the expansion and contraction of the balance spring under changing temperatures (see 'The key discovery', p94).

But it was H-4, a pocket-sized watch that weighed 'less than the brain that conceived it' – in the words of Rupert Gould's definitive study, *The Marine Chronometer* – that changed history. Sent by sea to Jamaica in 1761-62, H-4 was found to be just five seconds slow on arrival, corresponding to an error in longitude of just two-hundredths of a degree: well within the accuracy specified to win the £20,000 prize.

Naturally, the astronomers – led by the Astronomer Royal, Maskelyne – were not best pleased. The prize money was withheld by the Board of Longitude, while Harrison and his chronometers were subjected to increasingly severe tests in the 1760s. In 1772, Harrison's son made a personal appeal to King George III to test H-5, completed in 1770, in his personal observatory at Richmond. After an embarrassing hiccup in performance, traced to some nearby royal magnetic lodestones, H-5 proved itself accurate to within one-third of a second per day. With the King's advice and support, but after further resistance from the Board of Longitude, Parliament agreed to pay most of the money due to Harrison in 1773.

Two years later, not long before its inventor's death, Harrison's chronometer received an even greater accolade. Captain James Cook was the greatest explorer of his age. On his return from his second voyage to the Pacific, he pronounced that his chronometer – an exact copy of H-4 made by Larcum Kendall – "exceeded the expectations of its most zealous advocate and by being now and then corrected by lunar observations has been our faithful guide through all vicissitudes of climates." By the 1790s, marine chronometers had become standard equipment for naval captains. When HMS Beagle left Britain in 1831 to survey the world, carrying on board the young Charles Darwin, it took along no fewer than 22 chronometers. By then, Britannia really did rule the waves – thanks, in part, to its accurate measurement of longitude. ■

ANDREW ROBINSON is the co-author of *The Shape Of The World* (Rand McNally)

Find out more

BBC Watch *The Clock That Changed The World*, in which Adam Hart-Davis discusses the device that helped us measure longitude. youtu.be/T-g27KS0yiY