Topic Guide:

Sailing by the Stars

GCSE (9-1) Astronomy

Pearson Edexcel Level 1/Level 2 GCSE (9-1) in Astronomy (1AS0)

Sailing by the Stars

Contents

Specification Points

1.4 Be able to use the altitude and longitude co-ordinate system.

1.5 Be able to use the major divisions of the Earth's surface as astronomical reference points, including:

a Equator

…

f Prime Meridian

g North Pole

h South Pole

4.13 Understand the variation in the Sun's apparent motion during the year, particularly at the equinoxes and solstices.

4.15 Understand the difference in local time for observers at different longitudes.

4.16 Understand the use of time zones.

4.17 Be able to use data related to time zones.

4.18 Know that mean time at any point along the Prime Meridian is defined as Greenwich Mean Time (GMT).

4.20 Understand the principles of astronomical methods for the determination of longitude, including the lunar distance method.

4.21 Understand the principle of the horological method for the determination of longitude (Harrison's marine chronometer).

6.7 Understand the meaning of the terms:

a celestial sphere

b celestial poles

c celestial equator

6.9 Understand the use of the horizon co-ordinate system (altitude and azimuth).

6.14 Understand the diurnal motion of the sky due to the Earth's rotation.

6.18 Be able to find the latitude of an observer using Polaris.

Introduction

One of the reasons why civilisations have studied the Sun, Moon and stars has been to regulate systems of timekeeping and to navigate when sailing out of sight of land. This section of the Specification shows how the Celestial Sphere can be used to find direction and latitude and the difficulties involved in finding longitude. Some of the astronomical and horological solutions to this problem are also covered.

Positions on the Earth's Surface

Any point on the Earth's surface can be identified by giving two numbers – its Latitude and its Longitude:

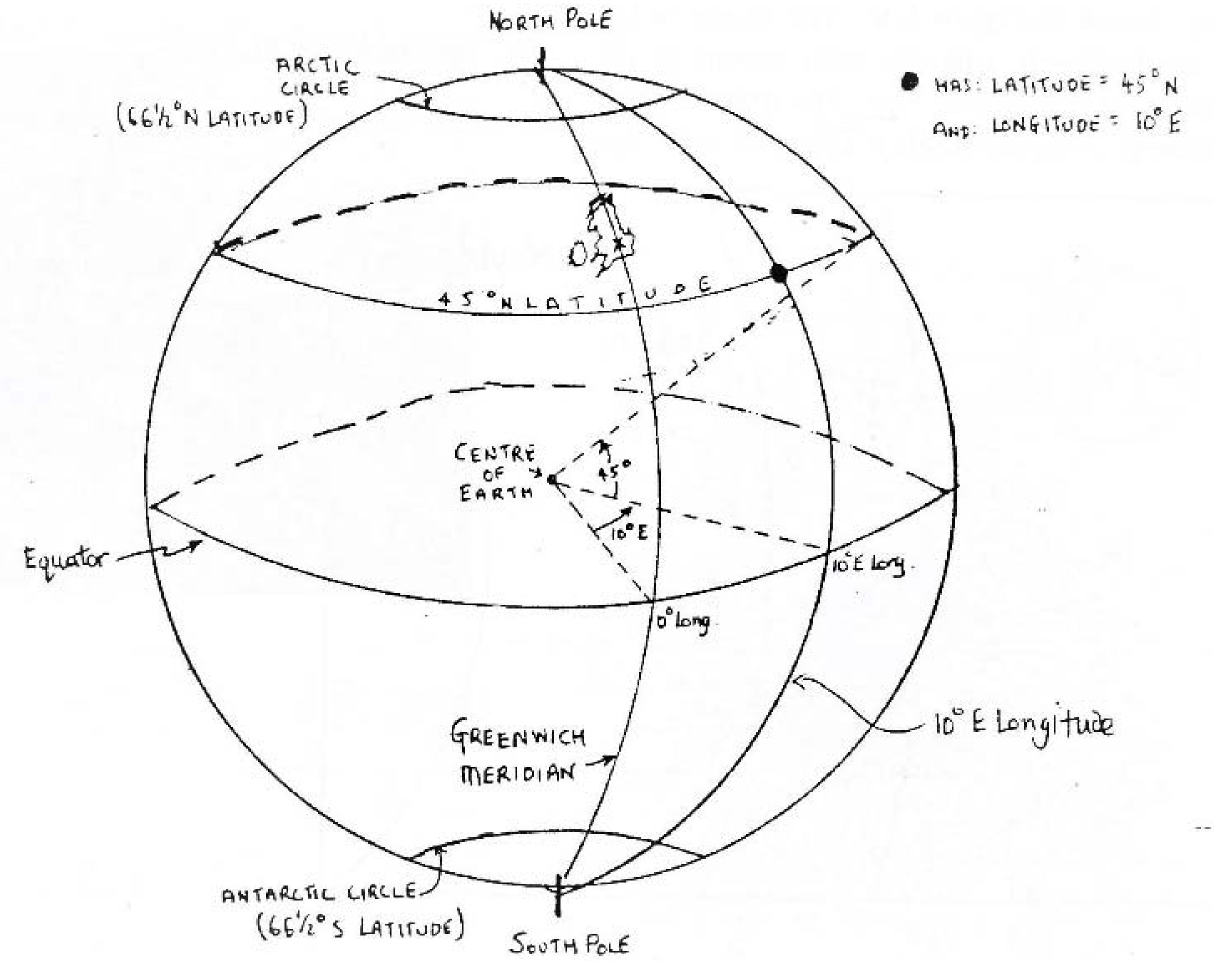


Figure 1: Latitude and Longitude. All points on the Earth's surface can be identified using two numbers – their Latitude and Longitude. The point marked ● for example, has a latitude of 45°N and a longitude of 10°E.

Figure 1 shows how Latitude and Longitude are used to give the location of a point on the Earth's surface.

Latitude measures how many degrees north or south of the Earth's equator a point is. Latitude is 0° for all points on the equator, 90°N for the North Pole and 90°S for the South Pole.

Longitude measures how many degrees east or west of the Prime Meridian a point is. It starts from 0° for all points on the Prime Meridian and increases to a maximum of 180° for points directly opposite the Prime Meridian, known as the International Date Line.

Figure 2a: The Prime Meridian. This line joins the Earth's North and South poles and runs through the Royal Observatory at Greenwich in south-east London. The meridian is marked with a metal strip across the courtyard of the Observatory. Observations of astronomical objects transiting the Prime Meridian, made using telescopes mounted along this line, formed the basis of Greenwich Mean Time for many centuries.

The Prime Meridian is a line on the Earth's surface joining the North and South poles through the Royal Observatory in Greenwich, UK.

Figure 2b: Prime Meridian markers: At a number of places between Peacehaven on the Sussex coast and Tunstall in the East Riding of Yorkshire, the position of the Prime Meridian is shown by a variety of marker posts and other monuments. This small post is in the village of Wyddial in north-east Hertfordshire. It was erected in 1984 as part of the commemoration of the centenary of the Prime or 'Greenwich' Meridian as it was referred to at the time.

Finding your Location on the Earth's Surface

Before the satellite age it was impossible to have a view of the Earth's surface such as that shown in Figure 1! Consequently, in places such as deserts, or when out of sight of land at sea, it has always been difficult to find one's latitude and longitude. For this reason, most early exploration of the Earth was restricted to voyages which could stay in sight of land.

Figure 3: Finding direction on the Earth can be difficult when out of sight of familiar landmarks. This is why one of the earliest reasons for studying the motion of the Sun and stars was to aid with navigation.

Astronomy provides a way of using the Sun and the stars to help find your position on the Earth's surface.

Finding Direction

Although magnetic compasses will point to the Earth's North Magnetic Pole[1], the Sun and the stars can be used to find the cardinal (compass) directions from any place on the Earth.

As Figure 5 shows, in the northern hemisphere of the Earth, the North Celestial Pole is clearly marked by the Pole Star, which means that the direction of the Earth's North Pole (and thus the other three points of the compass) can easily be found from the direction of this star in the sky.

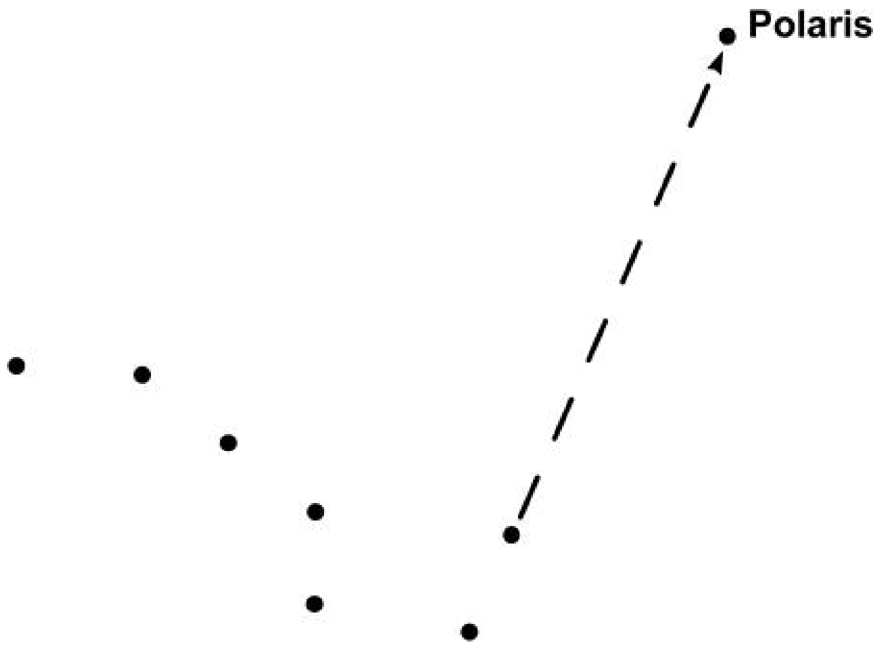


Figure 4: Using The Plough to find Polaris, the Pole Star. Following the line of the two bright stars, Dubhe and Merak, at the end of the 'blade' in the Plough asterism or the right hand edge of the 'pan' in the Saucepan asterism has helped navigators to find the Pole Star for thousands of years.

The 'Plough' asterism within the constellation of Ursa Major can be used to find the Pole Star, as shown in Figure 4.

[1] Which 'wanders' very slowly either side of the Earth's Geographical North Pole.

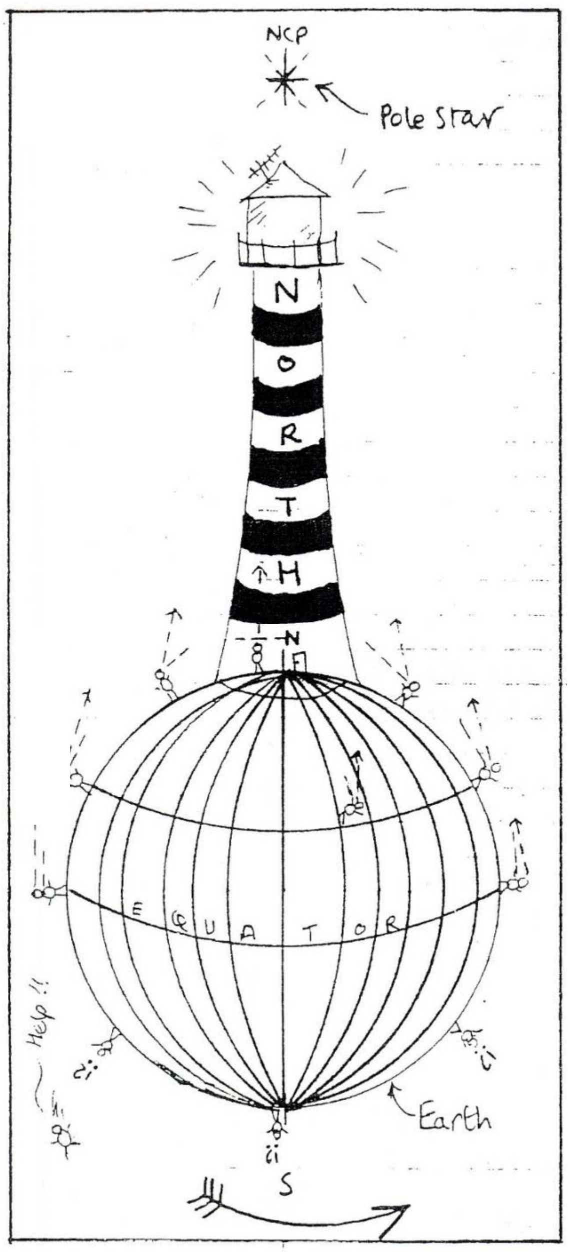


Figure 5: The Pole Star. One way of understanding the link between the Pole Star and directions in the northern hemisphere of the Earth is to imagine it at the top of a very tall lighthouse at the North Pole of the Earth. As a result, anyone on the Earth who is looking towards the Pole Star must be facing northwards. In addition, the angle of the Pole Star above an observer's horizon (its 'altitude') will be equal to the observer's latitude.

Finding Latitude

i) Using the Pole Star

As Figure 7 shows, the angle of the Pole Star above an observer's horizon (its 'altitude') will be equal to the observer's latitude. An observer at the North Pole (Lat. = 90ºN), for example, will see the Pole Star directly above their head, i.e. with an altitude of 90º. An observer at the Earth's Equator (Lat. = 0º) will only be able to see the Pole Star on their horizon, i.e. with an altitude of 0º and so on…

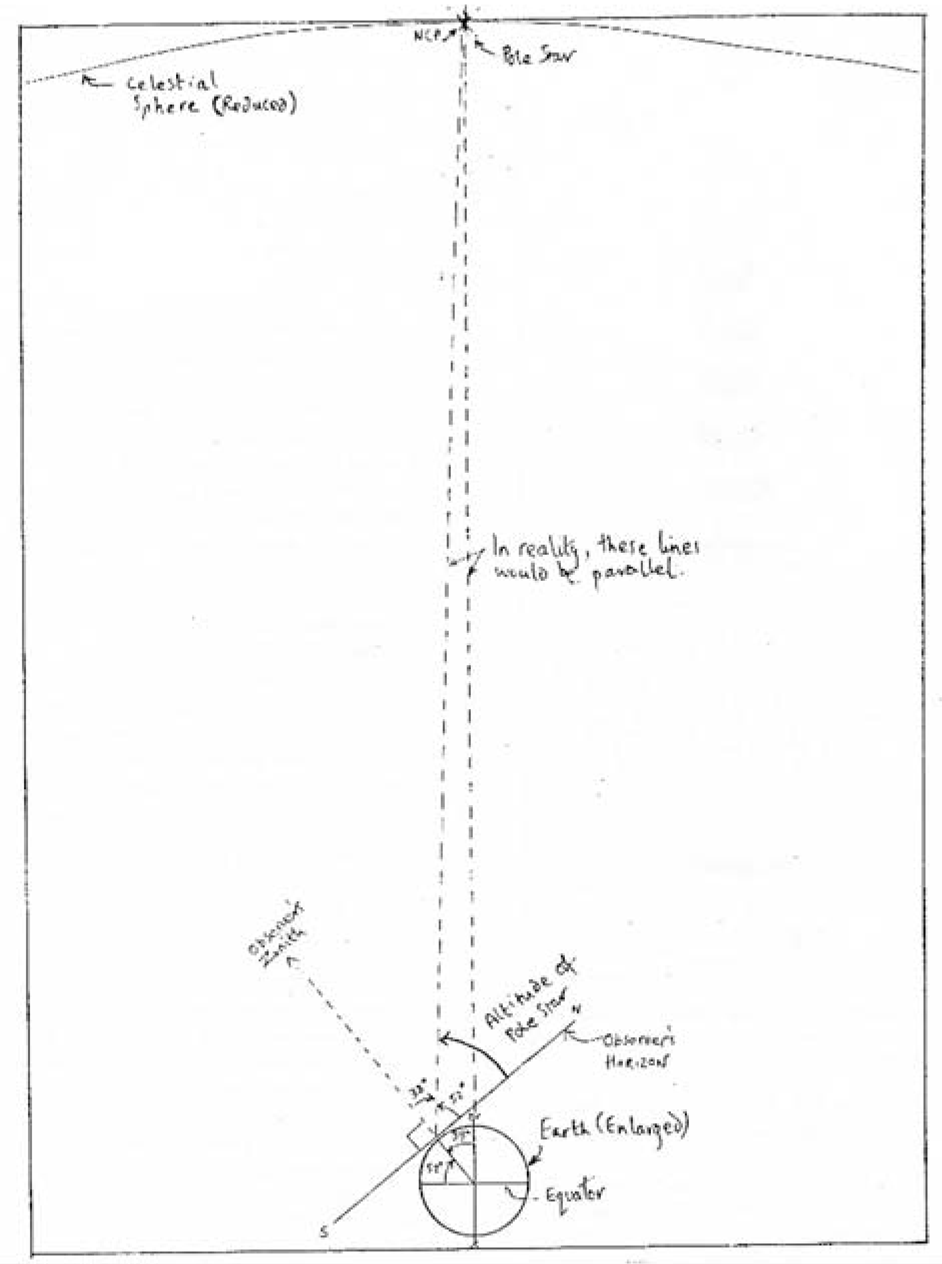


Figure 6: The Altitude of the Pole Star The altitude of the Pole Star (its angle above the horizon) will always be the same as the observer's latitude. On the scale of this diagram the Pole Star will effectively be an infinite distance away, making the two lines drawn to it almost perfectly parallel.

ii) Using the Sun

A second result of the tilt between the observer's horizon and the Celestial Sphere allows sailors to calculate their latitude by observing the midday Sun. As Figure 7 shows, the southern edge of the observer's horizon is tilted below the Celestial Equator by an angle equal to the observer's co-latitude (90° – their latitude).

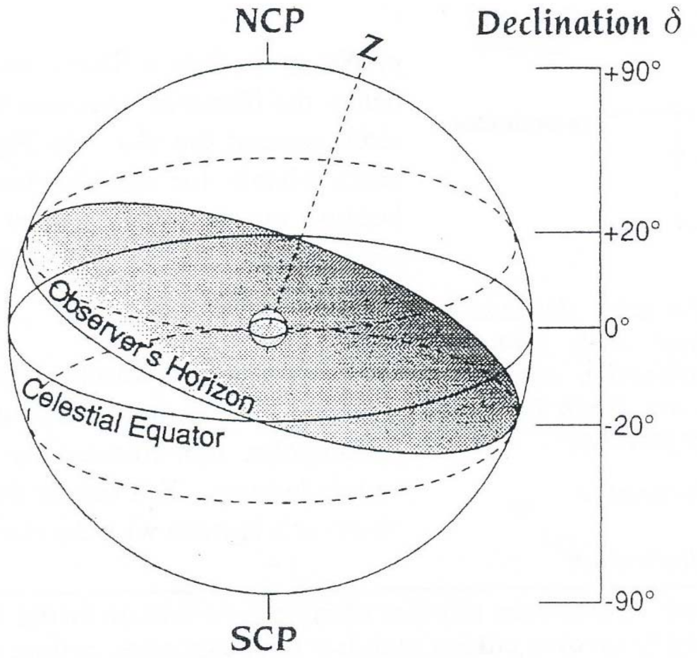


Figure 7: The Observer's Horizon and the Celestial Sphere. This diagram is drawn for an observer at a latitude of 70°N. This means that the observer's horizon is tilted at an angle of 20° (90° – 70°) to the Celestial Equator – their co-latitude. As a result, the North Celestial Pole (marked by the Pole Star) is always 70° above the observer's northern horizon and the highest point of the Celestial Equator (marked by the Sun at midday) is always 20° above their southern horizon.

In other words, the altitude of the highest point of the Celestial Equator, which will be on the observer's meridian, is always equal to their co-latitude. This means that when the Sun reaches its highest point in the sky at local noon, its altitude will be equal to its declination added to the observer's co-latitude, i.e.:

Altitude of Sun at noon = Declination of Sun + (90° – Observer's Latitude)

Consequently, sailors out at sea simply need to measure the altitude of the Sun at its highest point (noon) and look up the Sun's declination[2] for the day in question to then calculate their latitude.

On a day when the Sun is on the Celestial Equator (the Equinoxes, March 21st and September 21st), its altitude at midday will simply be equal to 90° – the observer's latitude.

[2] Since the Sun appears to move along the ecliptic every year, the pattern of the Sun's changing declination is the same every year and thus easily put into a simple table.

On 21st June, the Sun is at its highest point on the Celestial Equator, at a declination of 23½°. This means that the Sun's altitude at midday is equal to 23½° plus the observer's co-latitude.

On any day of the year, the observer's co-latitude is always equal to the Sun's midday altitude minus the Sun's declination.

For example, on March 14th, the declination of the Sun is -2° 45′, which means that the Sun is 2° 45′ below the Celestial Equator. If an observer measures the Sun's altitude at midday as 42°, then the angle between the Celestial Equator and the horizon must be 42° - -2° 45′ = 44° 45′ which is equal to the observer's co-latitude.

This means that the observer's latitude is 90° – 44° 45′ = **45° 15'**

Figure 8: Sundials. The gnomon or part of a sundial casting the shadow is aligned with the North Celestial Pole and therefore effectively points towards the Pole Star too. This means that its upper end (attached to the wall in this design of sundial) always points due North and is tilted at an angle equal to the latitude where it is sited (54° in this case).

Finding Longitude

As Figure 5 shows, moving to a different latitude on the Earth's surface changes the angle between your horizon and the Celestial Sphere. As a result, the Sun and all the stars (particularly the Pole Star) will appear to be at different angles above the horizon. This is why the Sun or the Pole Star can be used to find one's latitude using their altitude above the horizon.

However, moving to another location with the same longitude has no effect on the angle between your horizon and the Celestial Sphere. As a result, the Sun and all the stars make the same angles above the horizon and there is nothing to see in the sky to give any indication of your longitude.

For example, Moscow in Russia and Glasgow in the United Kingdom have almost exactly the same latitude of just under 56°N. However, they have very different longitudes, with Moscow being over 37°E of the Prime Meridian whereas Glasgow is 4°W of it. Since they have the same latitude, the path of the Sun across the sky each day will be the same in each city, as will the height of Polaris above the horizon and which stars are circumpolar etc.

The effect of their large difference in longitude will be that objects rise in the sky around 2½ hours earlier in Moscow than they do in Glasgow. However, in the days before telephones or any form of long-distance communication there would be absolutely no way of knowing this for observers in each of the two cities. There is nothing to see in the sky in Moscow which gives any indication that it is 37°E of Greenwich.

If a modern-day observer in Moscow was able to telephone an observer in Greenwich, then they would be able to establish that objects which rose some hours ago in Moscow were only just rising in Greenwich. This illustrates the close relationship between longitude and time – a connection which was to be used as one of the first reliable ways of measuring longitude.

Figure 9: The Greenwich Time Ball. Since its installation in 1833 this red ball on the roof of the Royal Greenwich Observatory has been dropped every day at 1pm as a signal to ships in the River Thames. It enabled ships' clocks to be set to the correct time, which is an essential requirement for correctly measuring longitude at sea.

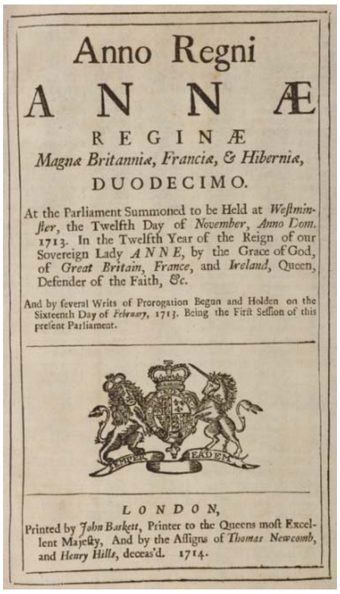
Finding Longitude at sea – the Longitude Problem

All the great sea-faring nations of the 17th and 18th century suffered severe losses of ships and sailors due to their navies' inability to measure longitude whilst out of sight of land.

Figure 10: The Wreck of the Association. In 1707, HMS Association and three other British warships were wrecked on rocks off the Isles of Scilly, with the loss of around 2000 men, making it one of the greatest naval disasters of its time. The primary cause was the fleet's inability to measure its longitude correctly.

The wreck of HMS Association in 1707 brought this issue to a head and, in 1714, Parliament passed The Longitude Act, offering a very large sum of money to anyone who could develop a reliable and practicable method which sailors could use to find their longitude at sea.

The method for finding longitude at the time was 'dead reckoning', where a ship's speed was simply multiplied by the time for which it had been sailing to give an estimate of its distance covered on a particular heading. Unfortunately the length in miles of each degree of longitude is different at different latitudes on the Earth's spherical surface, making this method extremely difficult to use accurately. The large number of ships lost each year showed that this method was very inaccurate.



Anno Regni
A N N Æ
R E G I N Æ
Magnæ Britanniæ, Franciæ, & Hiberniæ,
DUODECIMO.

At the Parliament Summoned to be Held at *Weſtminſter*, the Twelfth Day of *November*, *Anno Dom.* 1713. In the Twelfth Year of the Reign of our Sovereign Lady *ANNE*, by the Grace of God, of *Great Britain*, *France*, and *Ireland*, Queen, Defender of the Faith, &c.

And by ſeveral Writs of Prorogation Begun and Holden on the Sixteenth Day of *February*, 1713. Being the Firſt Seſſion of this preſent Parliament.

L O N D O N,
Printed by *John Baskett*, Printer to the Queens moſt Excellent Majeſty, And by the Aſſigns of *Thomas Newcomb*, and *Henry Hills*, deceas'd. 1714.

Figure 11: The Longitude Act. In 1714 Britain passed The Longitude Act which offered prizes equivalent to several million pounds today for a suitable method for finding longitude accurately at sea. Although Harrison's chronometers passed all the tests set for them by the Board of Longitude, he was only paid some of the prize money in 1773, following the direct intervention of George III.

Although the large prizes attracted a number of spurious suggestions[3], a number of serious methods were suggested, all based around the connection between longitude and time.

[3] The Wounded Dog being perhaps the most ridiculous.

Astronomical Solutions

The main astronomical methods for finding longitude relied upon using accurate observations of the Moon (or Jupiter's moons) against the background of the stars to calculate Greenwich Mean Time. Their practicability was therefore limited by the accuracy of observations which could be taken from the deck of a ship out at sea and by the ability of her sailors to perform often complex calculations.

i) **Jovian Moons**
Galileo had suggested that observations of the exact positions of each of the four Galilean moons of the planet Jupiter could be used to calculate the time at a ship's home port, from anywhere on the Earth. Although this was used successfully for measuring longitude on land, the practical problems of taking such accurate observations from a ship at sea meant that this method did not provide a solution to the Longitude Problem.

ii) **Lunar Occultation**
Edmond Halley worked on a method which involved using the times at which the Moon's disc covered (occultation) or came closest to certain bright stars. Despite extensive work by Halley to record the exact path of the Moon through the stars, this method was never made practicable for use by sailors. There was also the difficulty that many nights could go by without any lunar occultation taking place.

iii) **Lunar Distance**
This method involved comparing observations of the distances between the Moon and certain bright stars with tables of these 'lunar distances' compiled from Greenwich. Following extensive calculation, the observer's longitude could be calculated from these measurements. The German astronomer Tobias Mayer was one of the first to produce a set of tables of lunar distances which were sufficiently accurate for this purpose.

The Horological Solution

Alongside the various astronomical solutions to the Longitude Problem, there was a very simple solution which simply required a ship to carry a clock which kept an accurate record of Greenwich Mean Time throughout its voyage.

Since the local time at the ship's location could be found from straightforward observations of the Sun or stars, finding longitude became a simply matter of comparing local time with Greenwich Mean Time. The larger the difference between these two times, the greater the ship's longitude.

For example, imagine a ship carrying a clock accurately measuring Greenwich Mean Time. Sailors on the ship check the clock precisely at their local noon (when the Sun reaches its highest point in their sky) and finds it is reading 2:30pm.

Since the Earth turns through 360^o in 24 hours, each hour of time difference must represent $360^o/24h = 15^o$.

The ship must therefore have a longitude of $2\frac{1}{2} \times 15^o =$ **37.5°W**

(Since the ship is experiencing local noon some hours after it has clearly already happened in Greenwich, it must be west of Greenwich.)

Although in principle a simple method, the technological problems involved in making a clock which could keep sufficiently accurate time aboard a ship in rough seas for many weeks proved to be beyond almost all clockmakers of the time.

To understand the difficulty of the problem, it is important to remember that a sea voyage to the West Indies, for example, could take around seven weeks, during which time the ship could be completely out of contact with any means of checking their true longitude.

By the end of such a voyage, any clock on board would need to allow the ship's sailors to measure their longitude to within an accuracy of no more than 30km – roughly the distance of the horizon at sea. Any larger error could mean that the ship would then run the risk of being out of sight of its true longitude, which might be marked by something like the coastline, leaving the ship unable to decide whether it was East or West of its destination.

A distance of 30km at the Earth's equator is equivalent to a longitude difference of around 0.3^o. To be accurate to 0.3^o of longitude, the value of GMT on the clock would have to be within 1 minute of the true time back in Greenwich. Over a seven week period this means that the clock could not lose or gain more than one second per day!

This represented an accuracy many times better than even the most accurate land-based clocks of the day, with many clocks of Harrison's time losing more than ten minutes a day. It is not hard to see why almost no other clockmaker had even attempted to make a clock to solve the Longitude Problem.

John Harrison's Marine Chronometers

However, John Harrison, a Lincolnshire clock maker devised a number of original solutions to the problem of allowing a clock mechanism to keep almost modern-day levels of accuracy whilst being buffeted on board a ship for several weeks.

During his lifetime he developed several designs of 'marine chronometer', which became known as H1, H2, H3 and H4, all of which survive and can be seen on display in full working order at the Royal Observatory in Greenwich.

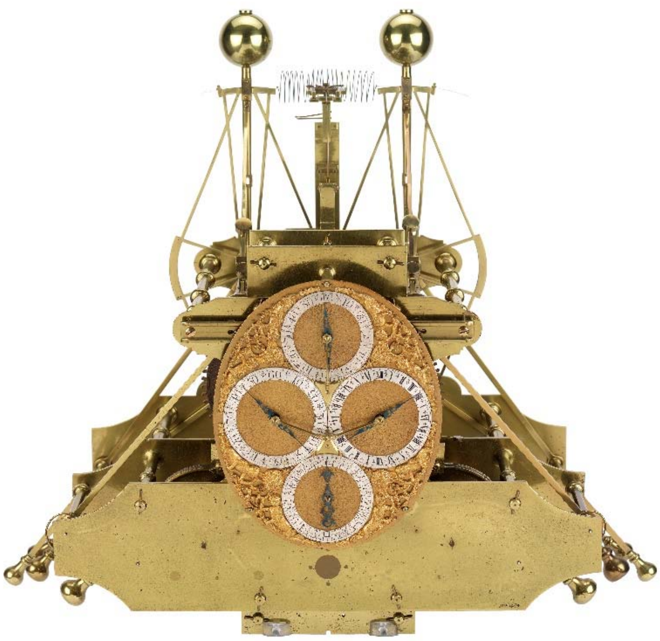


Figure 12: H1. John Harrison's first marine chronometer was able to compensate for the changing temperature during a long sea voyage and worked without any lubrication. Its two large connected balances meant that it was resistant to even the most violent movements of a ship. Despite some considerable success on its sea trials it was not sufficient to convince the Board of Longitude to award their prize money although they gave Harrison funds to support the development of H2. Restored to full working order in the twentieth century, H1 can be seen running at the Royal Greenwich Observatory in London. ©National Maritime Museum, Greenwich, London

Despite a number of successful sea trials of several of Harrison's marine chronometers, the Board of Longitude remained hopeful of a practicable astronomical method for determining longitude. As a result John Harrison and his son William were only paid their reward under the Longitude Act nearly fifty years after the first trials of H1 and only after direct intervention from King George III.

Figure 12: Site of John Harrison's house in Red Lion Square near High Holborn in central London, where he lived from 1739 and worked on the later marine chronometers such as H4.

Harrison's marine chronometer H4[4] provided the design for a number of marine chronometers which followed and allowed ships to determine their longitude quickly and accurately by comparing their local time with the Greenwich Mean Time shown on the chronometer. This method of finding longitude remained in use until the first radio time signals began to be broadcast at the start of the 20th century.

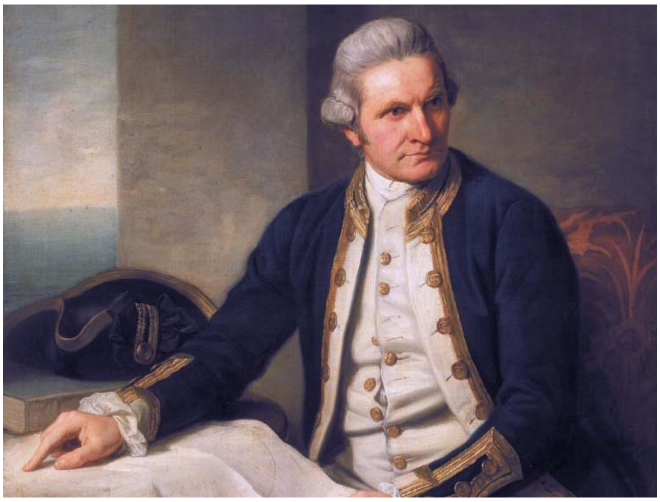


Figure 13: Captain James Cook (1728-1779) was Captain of a scientific expedition to Tahiti in 1769 to record the timing of the transit of Venus – an expedition which was also one of the first to allow Europeans to land in south eastern Australia[5]. The voyage also provided confirmation of the effectiveness of John Harrison's marine chronometer design as Cook took with him K1 – a copy of Harrison's H4 timepiece made by the London clockmaker Larcum Kendall. K1 can also be seen on display at the Royal Greenwich Observatory in London.

The fundamental link between time and longitude continues to be the basis for finding longitude as modern satellite navigation systems rely upon receiving very accurate time signals from orbiting satellites.

[4] Before his death in 1776 Harrison completed a second 'sea watch' known as H5, which is on display at the Worshipful Company of Clockmakers' Museum in the City of London.

[5] …and was considered too dangerous for the Astronomer Royal at the time (Nevil Maskelyne) to take part in, so the necessary observations were completed by the young astronomer Charles Green.

Further Support

The following websites contain further information about the topics covered by this Support Sheet:

1. Almost all the people and places described in this sheet have individual entries in Wikipedia.

   www.wikipedia.org

2. The Royal Astronomical Society's Leaflets for Schools contain material to support the teaching of several of the topics covered by this sheet.

   www.ras.org.uk/publications/other-publications

3. The Royal Greenwich Observatory website contains resources relevant to many of the topics covered in this sheet and was itself the site of the work of some of the astronomers mentioned. It is therefore a unique location for students of GCSE Astronomy to visit.

   www.rmg.co.uk/royal-observatory

4. The Educators section of the NASA website contains a wide range of resources to support students and teachers learning about many of the astronomical topics covered in this sheet.

   www.nasa.gov/audience/foreducators/index.html

5. The British Horological Institute's website is the place for those interested in the details of how clock mechanisms have been engineered over the years, essentially to replicate the astronomical motions which are the foundation of our systems of time measurement.

   www.bhi.co.uk

6. The British Sundial Society's website and magazine cover the detailed workings of sundials as one of the first means for using astronomical patterns to provide a measure of time.

   www.sundialsoc.org.uk

7. The Worshipful Company of Clockmakers' museum in the City of London is a unique collection of the work of London's great clockmakers of the eighteenth century, many of whom were engaged with attempting to design clocks to solve the Longitude Problem. It also includes John Harrison's final clock – H5.

   www.clockmakers.org

Checkpoint Questions

1. Write a definition of each of the following terms:
    a. Latitude
    b. Longitude
    c. Prime Meridian
    d. Celestial Pole
    e. Altitude
    f. Local Noon
    g. Greenwich Mean Time (GMT)

2. Since the altitude of the Celestial Equator on an observer's meridian is always equal to 90° – observer's latitude, calculate the altitude of the Sun at midday in each of the following cases:
    a. From a latitude of 55°N on a day when the Sun's declination is 20°.
    b. From a latitude of 20°N on a day when the Sun's declination is 21°.
    c. From a latitude of 80°N on a day when the Sun's declination is -15°.

3. Use a similar method to that used in question 2 to find the observer's latitude in each case:
    a. The Sun has an altitude of 56° at noon on a day when its declination is 16°.
    b. The Sun has an altitude of 10° at noon on a day when its declination is -6°.
    c. The Sun has an altitude of 90° at noon on a day when its declination is 19°.

4. A ship sets sail from Greenwich carrying a clock which accurately shows Greenwich Mean Time (GMT) throughout its voyage. Some days later the clock reads 10.40am when it is local noon at the ship's location.
    a. Calculate the difference between the ship's local time and GMT.
    b. Use your answer to (a) to calculate the ship's longitude.
    c. State whether the ship is East or West of the Prime Meridian.

5. A ship sets sail from the island of St. Helena in the Atlantic Ocean (Latitude= 15° 56′ S; Longitude = 5° 45′ W), carrying an accurate clock set to the time in St. Helena. Some days later the clock is checked at the ship's local noon and found to read 11:37am.
    a. Use this information to find the ship's longitude.
    b. State whether the ship is now East or West of St. Helena.

6. A ship makes a two-week voyage at sea with a clock on board which is unfortunately inaccurate by two seconds in every hour. The ship sails along the equator, where the Earth has a circumference of 40 000km. If the inaccurate clock is then used to determine the ship's longitude at the end of its two-week voyage, calculate:
    a. The error in the calculated longitude value.
    b. The number of kilometres by which the ship's calculated position will be wrong.