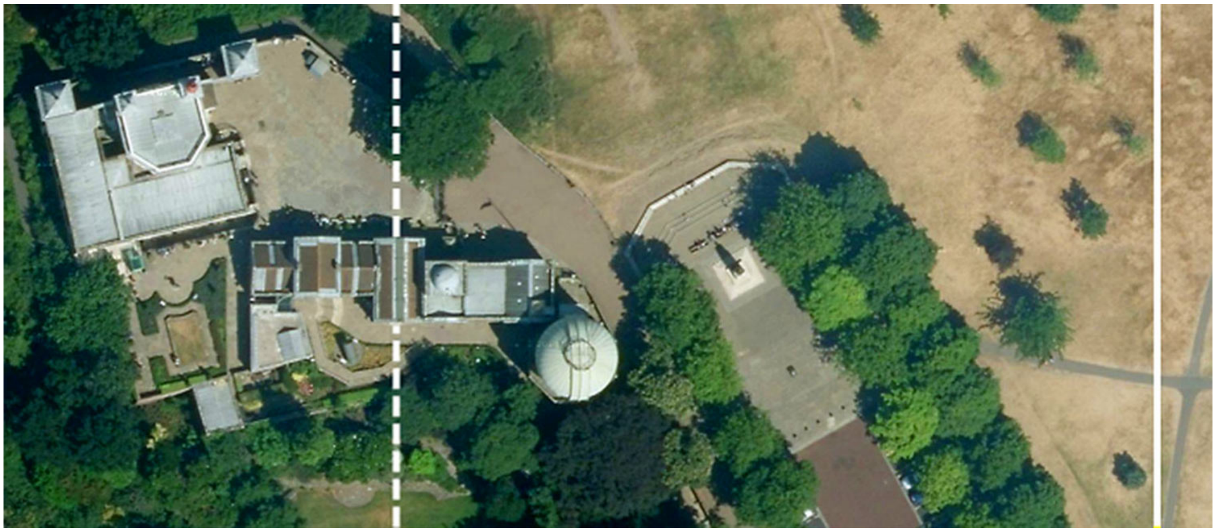
Knowing (exactly) where you are is not that simple!



Many projects need to accurately locate the position of property lines and facilities, but achieving this is far from straightforward.

One reasonably well-known example of this challenge is the Prime Meridian at Greenwich. This historic meridian is a geographical reference line that is marked on the ground, and passes through the Royal Observatory, in Greenwich, London (the dashed line above). The Prime Meridian used by your GPS is the solid line. The objective of this article is to explain why these are different!

The Royal Observatory was established in 1675 by King Charles II to support the work of the Astronomer Royal. In addition to astronomical studies, two of the challenges addressed by for the Astronomer Royal over the centuries was setting the time for the City of London and solving the 'Longitude Problem'.

Greenwich Mean Time (GMT) is based on the solar noon as measured at the observatory, but the exact position of this Prime Meridian line was only established by Sir George Airy in 1851[1]. The observatory could be seen from most parts of the city and river and the time of noon each day was communicated to the rest of London and shipping in the river by lowering a 'time ball'. The 'time ball' is still dropped at noon, but these days is primarily a tourist event.

Since 1847 the use of this GMT has been extended to standardize time across the United Kingdom initially to facilitate railway timekeeping. Prior to 1847 local time was determined by people setting their watches and clocks to match the time displayed on the church, or town, clock which was set by regular observations of the sun at that location. This resulted in a difference of several minutes between the East and West coasts[2].

1 As the ability to accurately measure time improved, the need for a precise baseline became more important to remove any error caused by the positioning the measuring equipment.

2 For more on ***measuring time*** see: https://mosaicprojects.com.au/Mag_Articles/AA031_Measuring_time.pdf

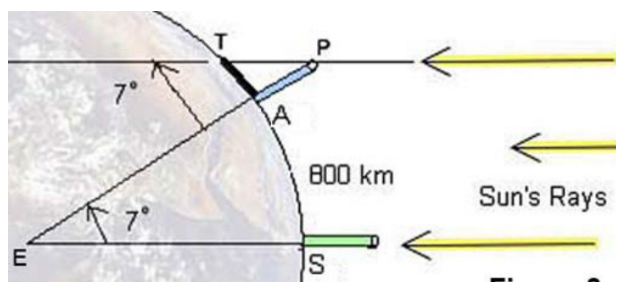
The longitude problem was more complex[3]. The measurement of latitude (how far north or south of the equator you are) and longitude (how far East or West you are of a given meridian) is important to both cartography and navigation. Latitude is relatively simple to calculate by knowing the date and measuring the height of the sun at noon, which in turn is the highest point the sun will reach above the horizon on that day (its maximum azimuth) so you do not even need a clock, just a series of measurements using a theodolite or sextant. However, to calculate latitude, you need to know the difference in time between noon at the baseline meridian of your charts and local noon. Measuring the sun's maximum azimuth is at your location is straightforward, but before the development of chronometers, accurately determining the time difference between where you are and the time at a location hundreds, or even thousands, of miles away was a challenge.

To overcome this problem a massive set of tables to facilitate the calculation of longitude using the moon were compiled at the Royal Observatory in Greenwich from 1766 onwards, published annually as part of the Nautical Almanac. By 1884, over two-thirds of all ships navigating the world's oceans used Greenwich as the reference meridian on their charts and maps. This widespread use of The Nautical Almanac was one of the principal reason Greenwich was selected as the world's base meridian by the International Meridian Conference in 1884.

However, as the picture above shows, the modern IERS Reference Meridian used by GPS and other systems is approximately 102 meters east of the original meridian. How did this occur? – It is a long story that intertwines astronomy, map making, navigation, and time keeping.

Calculating the size of the earth

The Ancient Greeks, and most other early civilizations were aware that the earth was a sphere, and assumed incorrectly, that the sun, moon, stars, and planets orbited the earth. By the third century BCE, the relationships between the different orbits and other astronomical data had been collected by observation for more than 3000 years.



But it was not until the Greek librarian and astronomer *Eratosthenes of Cyrene* (276-195 BCE)[4] devised an ingenious method for measuring the circumference of the Earth a reasonably accurate assessment of its size was achieved. *Eratosthenes* had learned that on the first day of summer a vertical staff in the Egyptian town of Syene cast no shadows. In contrast, on that same day in Alexandria a vertical staff did cast a shadow. With a few measurements, some assumptions, and a little geometry, he was ready to approximate the circumference of the Earth.

Eratosthenes made five assumptions:

1. That Alexandria and Syene lie on the same meridian.
2. That the light rays from the Sun striking the Earth are parallel.

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[3] For more on ***the longitude problem*** see: https://mosaicprojects.com.au/Mag_Articles/AA031_Measuring_time.pdf

[4] *Eratosthenes of Cyrene* was one of the many intellectuals based at the Great Library of Alexandria. For more on this amazing facility see: https://mosaicprojects.wordpress.com/2023/01/30/the-great-library-of-alexandria-the-first-google/

3. That the distance between Alexandria and Syene is 5000 stades.
4. That the angle formed by the shadow and the staff in Alexandria at the summer solstice is equal to 1/50th of a circle.
5. That the Earth is a sphere.

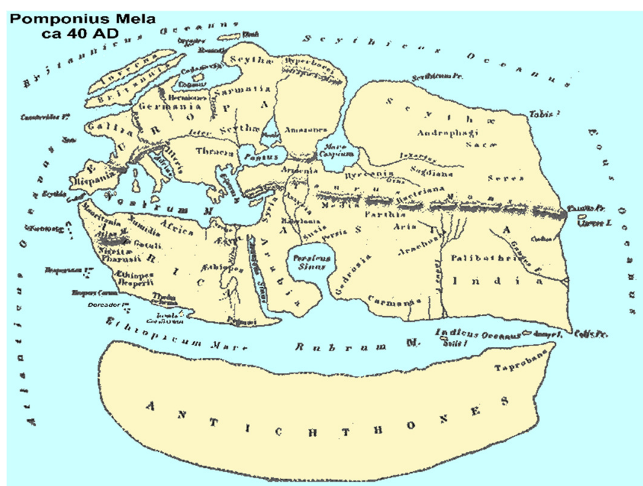
None of these assumptions are correct, but all are close enough to allow him to make a reasonably accurate calculation of the earth's circumference at 252,000 *stades*. Depending on the length of a *stade* used (there were different *'stades'* in use), this equates to 44,450 kilometres which is within 11% of the actual measurement today[5]. The next requirement was to divide the surface of the earth into defined segments with lines that can be used as reference points for mapping and navigation. A few centuries later Marinus of Tyre refined this estimate to a length of 180,000 stadia for the equator, roughly corresponding to a circumference of the Earth of 33,300 kilometres (20,700 mi), about 17% less than the actual value.

Latitude and Longitude

In the same time period, Greek astronomers normalized the lines of latitude and longitude to encompass the full 360 degrees of the earths globe and divided the day into 24 hours of equal length.

Eratosthenes used a sexagesimal system to divide a circle into 60 parts in order to devise an early geographic system of latitude, with the horizontal lines running through well-known places on the earth at the time. A century later, *Hipparchus* normalized the lines of latitude, making them parallel and obedient to the earth's geometry. He also devised a system of longitude lines that encompassed 360 degrees and that ran North to South, from pole to pole. He also proposed dividing the day into 24 hours of equal length. The 360 degrees of longitude corresponds to 24 hours meaning that the local time (or sun time) changes by four minutes for each degree of longitude you travel east or west.

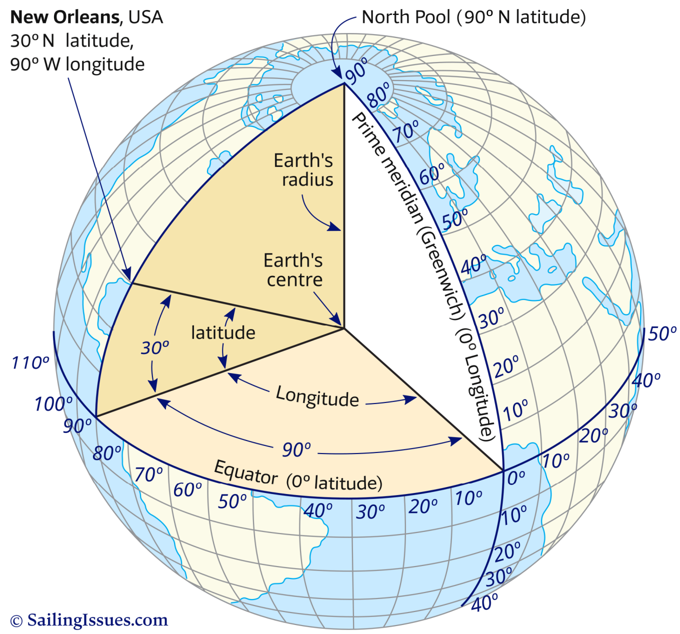
Marinus of Tyre (c. 70–130 CE) was a geographer, cartographer, and mathematician, who founded mathematical geography. He introduced improvements to the construction of maps and developed a system of nautical charts. His chief legacy is that he was the first to assign to each place a proper latitude and longitude. His zero meridian ran through the westernmost land known during his time, the Isles of the Blessed, around the location of the present-day Canary or Cape Verde Islands, and his maps were the first in the Roman Empire to show China at the other extreme. He used the parallel of Rhodes for measurements of latitude. Marinus also coined the term Antarctic, referring to the opposite of the Arctic. Marinus' geographical treatise (C. 114 CE) provided the underpinnings of Claudius Ptolemy's influential Geography, but the work is lost and known only from Ptolemy's remarks[6].



[5] For more on Eratosthenes of Cyrene see: https://www.maa.org/press/periodicals/convergence/eratosthenes-and-the-mystery-of-the-stades-introduction

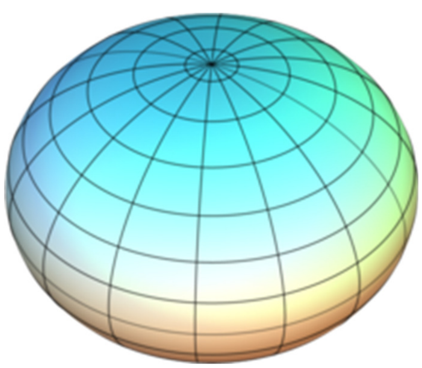
[6] These developments were centered around the Great Library of Alexandria, see ***The Great Library of Alexandria – The first Google?***: https://mosaicprojects.wordpress.com/2023/01/30/the-great-library-of-alexandria-the-first-google/

In his treatise Almagest (c.150 CE), Claudius Ptolemy explained and expanded on this work by subdividing each of the 360 degrees of latitude and longitude into smaller segments. Each degree was divided into 60 parts, each of which was again subdivided into 60 smaller parts. The first division, partes minutae primae, or first minute, became known simply as the minute. The second segmentation, partes minutae secundae, or second minute, became known as the second[7].



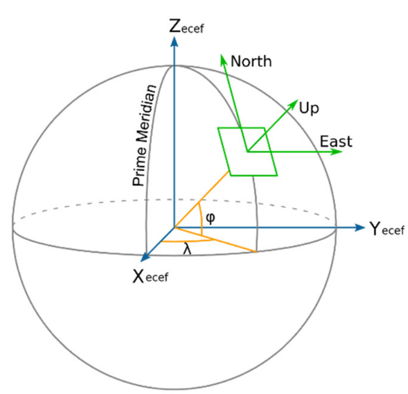
This work created the Degrees, Minutes, and Seconds of latitude and longitude we still use today. The base meridian for latitude was set at the equator, but different peoples and countries chose different baselines for calculating longitude. Then, as outlined above, the world eventually agreed to standardise the baseline for longitude at Greenwich in 1884. This system worked effectively for most of the next century.

GPS and the shape of the earth



As geographic measurements became more accurate in the late 17th century it was discovered the earth was not a perfect sphere, rather observations and calculations determined that its shape was an oblate spheroid. This did not change the relationship between latitude, longitude, and time, but it did affect map making and surveying.

The first assessment of the true shape of the earth was made by Sir Isaac Newton. He deduced Earth's shape theoretically based on the planet's speed of rotation and gravity, and estimated that the equatorial semiaxis would be 1/230 longer than the polar semiaxis (true value about 1/300). This finding was included in his *Principia*, published in 1687. Today the equatorial bulge at Earth's equator is measured at 26.5 miles (42.72 km). But this shape is only an approximation, the actual shape of the earth surface undulates and changes over time.



Before the use of satellites to measure the earth (and the need for navigation in near-earth orbit, different countries calculated reference grids based on a smoothed surface curvature, that approximated of the shape of the earth where they were located. These national survey grids have been adapted and updated over time.

7 For more on the development of time zones and the work of the Ancient Greeks see: https://mosaicprojects.com.au/PDF_Papers/P185-The_origin_of_calendars.pdf

In Australia, the original 1831 survey used the longitude at Parramatta Observatory and latitude determinations at Lake George, Warrawolong as the grid datum. More recently, the Australian Geodetic Datum 1966 (AGD66) used the Johnston Geodetic Station in the Northern Territory as the origin and the Australian Map Grid (AMG) as a projection.

After a number of other proposals and changes, in November 1994 the GPS-derived coordinates for the Australian Fiducial Network (AFN) were adopted, allowing Australia to position itself within a truly global mathematical framework and minimising the distortions introduced by deflection of the vertical, refraction and other phenomena in our physical world. These coordinates defined the Geocentric Datum of Australia 1994 (GDA94) using the reference ellipsoid GRS80 (Geocentric Reference System 1980).

But, Australia's physical position on the Earth has shifted north-east some 1.5 metres since 1994 due to tectonic motion while positioning accuracy has improved. Further distortions in the original GDA94 adjustment of up to 0.3 metres are apparent in NSW caused by changes in the physical shape of the continent.

To overcome these problems, in May 2015, the Intergovernmental Committee on Surveying and Mapping (ICSM) endorsed a "two-frame" datum modernisation strategy to support current and future positioning needs. The first of the two frames, the Geocentric Datum of Australia 2020 (GDA2020), is a new, static reference frame defined by 109 state-of-the-art GNSS reference stations across Australia, and propagated through the Australian State and Territory survey networks through a combined national least squares adjustment of approximately 2,000,000 measurements across 250,000 survey marks. This system is tied to the physical land mass of Australia.

The second of the two frames, the Australian Terrestrial Reference Frame (ATRF) is a time-dependent reference frame for high-precision applications only. ATRF is available through Geoscience Australia and is tied to the astronomical framework used by GPS. Most other advanced countries have followed a similar path.

The Greenwich Meridian v the GPS Meridian

Returning to the initial problem outlined in the opening paragraphs. The problem with the Greenwich Meridian of 1884 was that it was based on measurements from a telescope situated in a particular location, which did not account for the physical characteristics of the earth. In addition to the earth being slightly squashed at the poles, its mass is not distributed evenly. While neither factor is large, they do change the perceived effect of gravity at your location. This means that measurements carried out at one specific location are not necessarily accurate for other locations.

A 2015 study suggests that the astronomers who calibrated the telescope 1884 did so without accounting for these factors. They used a pool of mercury to identify the exact direction of Earth's gravity and, assumed this pointed to the planet's centre. However, they could not take into account local distortions of gravity caused by the shape of the earth, which caused the telescope to be slightly off vertical. The tectonic plate on which Greenwich is situate is also moving so while the Greenwich Meridian has not moved in relation to the observatory buildings, the observatory buildings have moved in relation to other place on earth.

Modern mapping and navigation systems use the WG S 84 meridian which has its base point set in the USA. WG S 84 is a global datum based on calculations of the earth's centre of mass and allows for the fact the earth is not a smooth oblate spheroid. WG S 84 measures its vertical axis from space in a straight line directly through the centre of the Earth, effectively removing the gravitational effects of mountains and other terrain.

In setting up this system, the calculations were based on the surveyed longitude of the Laboratory's site in Maryland where the work was being done, as measured in the North American Datum (NAD27). This became its assumed longitude in the first World Datum. It was this pragmatic adoption of the longitude coordinate on one ellipsoid as the assumed value on another that has caused the apparent shift not only in the position of the Meridian, but also of all other locations in the world.

The mathematical consistency of WG S 84 also causes problems. As tectonic plates move at a pace of a few centimetres per year, the datum remains in place in relation to the centre of Earth. Which means it will slowly move over the Earth's surface, rendering any fixed markings obsolete after just a few years. This shift is the reason Australia now has the two frames of reference outlined above for surveying – which one is best to use depends on the purpose of the survey.

Conclusions

The Greenwich meridian differs from the one used in GPS and other systems by about 102 meters because the calculations to determine the Meridien are based on different presumptions. The difference is in part due to the uneven shape of the earth and in part due to continental drift. Land surfaces continually move and the relationship between the UK and the USA will have changed appreciably since 1884 and continue to change year-on-year. In the modern world both time and geographic location are based on calculations rather than the physical geography of the earth’s surface, but the boundaries of the land you own (or are working on) do not change they are physically part of the earth’s surface.

So, answering the question *‘where in the world are you?’*, accurately can be remarkably difficult and will change over time. The issues discussed in this article will not have much effect on the outline of a neighbourhood block, surveyed from marks established in the locality, but will affect projects like Inland Rail which stretches over 1,700 km from Melbourne to Brisbane.

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