Astronavigation – finding our way by Sun, Moon and Stars

John S. Reid

This piece is based on notes for a public talk given on 31st Jan 2015. It was accompanied by PowerPoint slides and the use of Stellarium sky simulator[1] software showing the sky around the days of the talk to illustrate some of the points. The text also refers to some flash simulations from the University of Nebraska-Lincoln that can be downloaded. At the end of the PowerPoint the use of the StarStruck app on a smartphone was shown. The text here includes some screenshots from Stellarium at a reduced scale that were incorporated into the PowerPoint but they do not show the detail visible at the talk. The text below includes a few footnotes that were not part of the lecture. Not all the points in the text were made in the talk.

Introduction

Astronomy today is all about what the planets, moons and the rest of the solar system are like, what stars are, how they work, how they're organised into galaxies and galactic clusters, and much more - curiosity on a cosmic scale. It's great. I love it but astronomy has a very practical side too. In the past national observatories were built, sailors and explorers learnt about astronomy and many books were written about it because astronomy made quite accurate navigation possible, especially navigation at sea. The old methods, before satellite navigation took over in this century, still work. How?

I want to show the ideas behind some of the astronavigation methods. In practice to get the most accurate results various so-called 'corrections' to the observations have to be made - for example, correction for height above sea level; correction for distortion due to the atmosphere; correction of lunar observations because the surface of the Earth is nearer the Moon than the centre of the Earth. I'm not going to describe these corrections and when they are needed. They are detail required if you want the best accuracy.

Astronomy provides directions

Let's start. You're in a strange place or out of sight of land at sea. How do you know where North, East, South and West are? Every boy or girl scout would probably bring out their compass but our ancestors navigated before the compass was invented. Even after its invention, for various reasons a compass can sometimes give you a misleading answer. Do it right, and astronavigation won't mislead.

Directions during the day

During the day, due South in our hemisphere is determined by the direction in which the Sun is highest in the sky. It's the same all year around. Another way of saying the same thing is that due South is the direction of the Sun when the shadow of a fixed pole is at its shortest. Once you have found due South, then North is in the opposite direction and you have East and West as well.

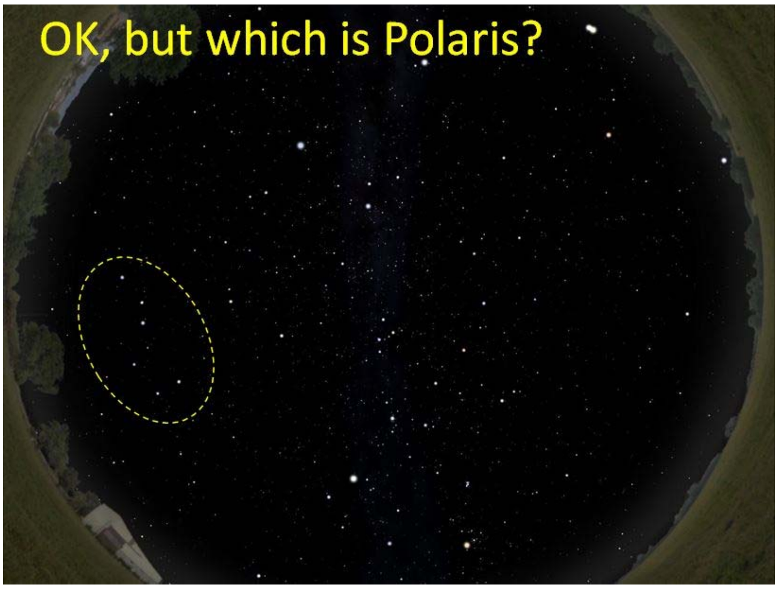
The association of the Sun and South is such that if you are lost in an unfamiliar European or North American city on a dull day, then look at the way the expensive houses are facing and that is probably South.

The Sun rises in the East and sets in the West only when it is directly above the equator. If you're a good bit nearer the equator than we are here, then the Sun rises not too far from East minus the sun's declination and sets not too far from (West + declination). Among the Pacific islands, for example you can get a good idea of East and West near dawn and dusk and bright Venus will extend this hint into darkness.

Directions at night

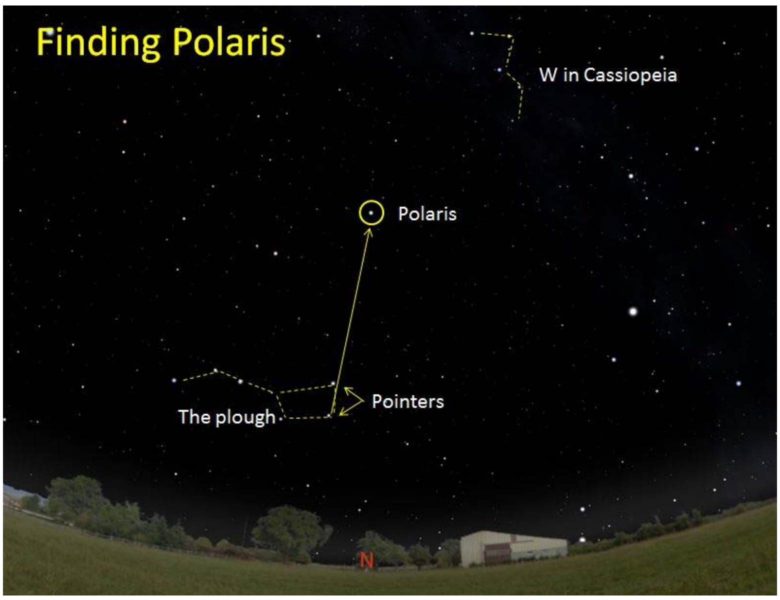
At night, the stars wheel around the sky. As for the Sun, any planet or the Moon or star in that part of the sky will be at its highest above the horizon when it is due South. If you have a device for measuring angles of elevation, then you can find due south. By speeding up time with Stellarium this maximum altitude is seen clearly.

There is an even easier way. In the Northern hemisphere the pole star (Polaris) is almost at the centre of the wheeling circle of stars so to within a degree or so you get due North, once you can spot Polaris.



Which direction is north?

Lie on your back and look up at a cloudless sky (more likely on a boat than on land) and you see just a mass of stars. Which one is Polaris? You need a guide, a starting point to recognise. The best guide is to find the asterism of 'the plough', or the big dipper as it's sometimes called. It's one of the few features in the sky that many people recognise. You can use other stars to find directions but you need to know the time of night since they swing around the celestial pole.



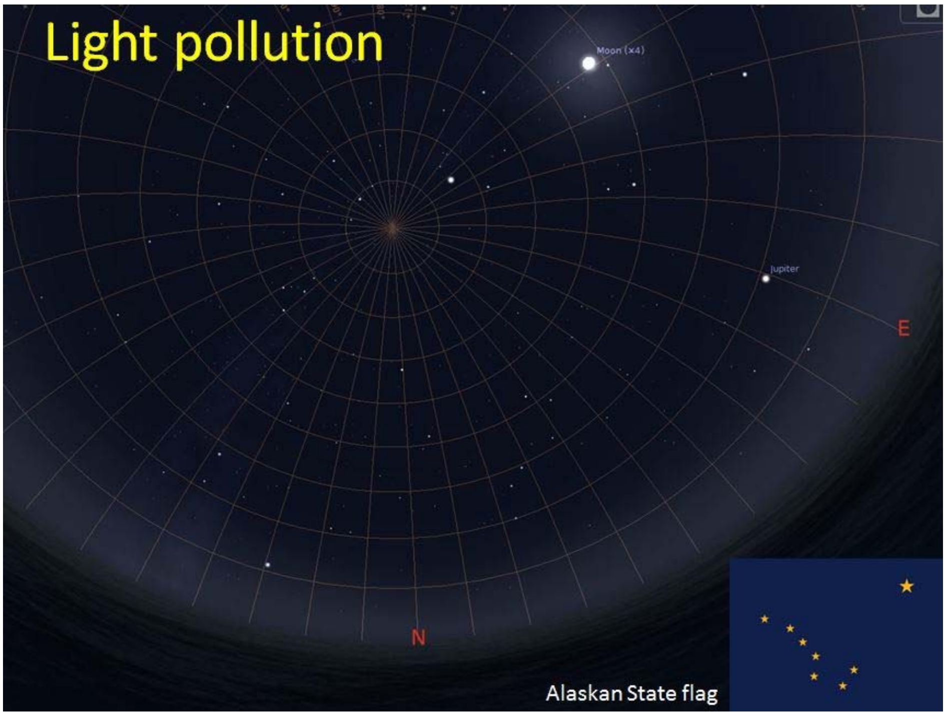
Finding Polaris

1. Locate the plough – it may

be on its side or even upside down so it may not leap out at you.

2. Find the so-called pointer stars (Merak (furthest from pole) and Dubhe (nearest)).
3. Run a line from the pointers and the first bright star you'll see, some distance away, is Polaris. Some people find the W asterism in Cassiopeia easy to spot. It's on the other side of Polaris from the plough.

Light pollution



The plough is composed of some of the brighter stars in the sky so if faint stars are washed out by local light then you'll still be able to find the plough. The slide shows the sky at 7.30 pm tonight.

When I was learning where stars were in the sky for my navigation exams we had to know about 20 of the brightest stars. The School of Navigation in Kings Street (long since closed) had a planetarium – it's the one that's now in Aberdeen College. It was much more recently that I found out that the State Flag of Alaska features the Big Dipper and Pole Star.

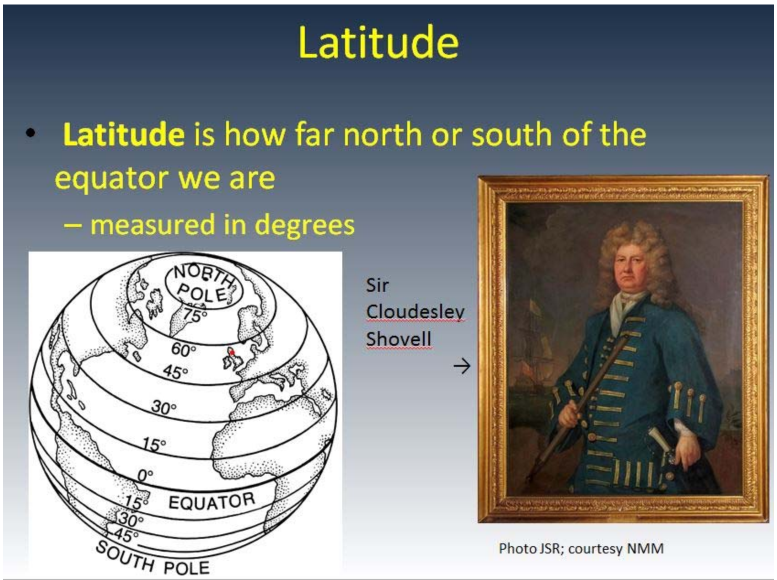
Finding which is North, East, South and West is a good start for any navigator.

Where am I?

There are 2 main problems in navigation: finding the right direction to go in and finding where you are just now. The Sun and the stars solve the problem of direction, if you can see them. What about finding where you are? The answer is to find your latitude and longitude. Every place on Earth has a latitude and a longitude – latitude and longitude are marked on the sides of all marine charts. I've two examples here that can be seen afterwards. Unfortunately they aren't marked on the ground or on the sea. (I rather like the idea of a network of buoys anchored at sea all over the globe with signposts marking their latitude and longitude, but it was never so). Latitude and longitude are found by astronomy. Latitude and longitude are central to our story so I'll remind you what the difference is.

Latitude

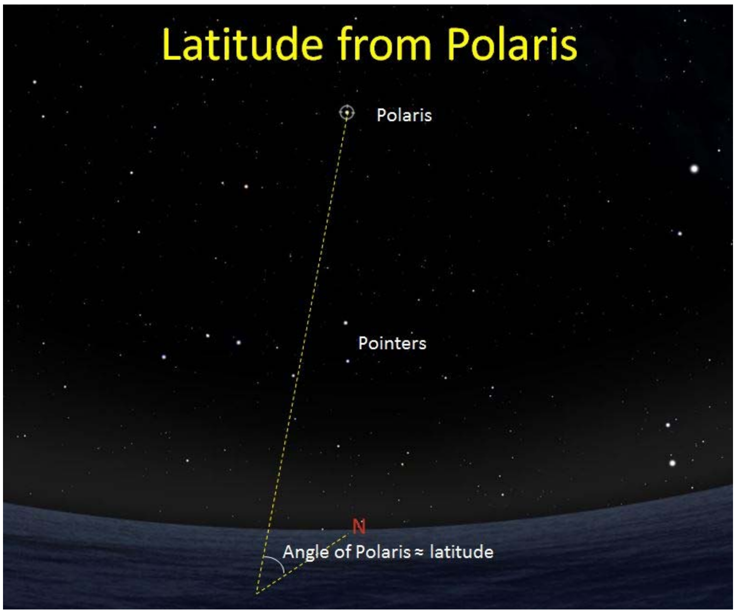
Latitude is how far North of the equator we are. The equator is 0° N. It is the obvious zero. Here in this building we are 57.16775° N according to Google Earth[2]. Lines of latitude are circles around the globe and get smaller as we go North.



Geographers and sailors went on about the importance of knowing latitude and longitude many centuries ago but it took numerous catastrophes at sea to convince societies at large that something should be done to improve our knowledge of finding these. I'll tell you the story of the catastrophe that motivated the British government.

At the beginning of the 18th century, the Commander-in-Chief of the British fleets was Admiral Sir Cloudesley Shovell, whose portrait in the National Maritime Museum shows him in masterful pose, possibly holding one of the latest scientific tools to assist marine navigation, a telescope. Cloudesley Shovell had a significant impact on the development of astronavigation, though that was not his intention. Returning home from an encounter with the French Navy on 22nd October 1707 with five Royal Navy warships under his command, after a rough sail north he approached the English Channel in fog, as daylight faded. The story goes that a young sailor presented himself to the commander, questioning the decision of the navigator to steer the fleet in the direction it was making. Cloudesley Shovell acted promptly. He hanged the sailor as an example to the crew that the insubordination of querying the commands of his officers would not be tolerated. If true, his arrogance and navigational misjudgement were quickly revealed, for 4 of his 5 warships were wrecked that foggy night on the Western rocks of the Scilly Isles; almost 2000 men lost their lives, Cloudesley Shovell amongst them. This was a high price to pay for not knowing their latitude and longitude[3].

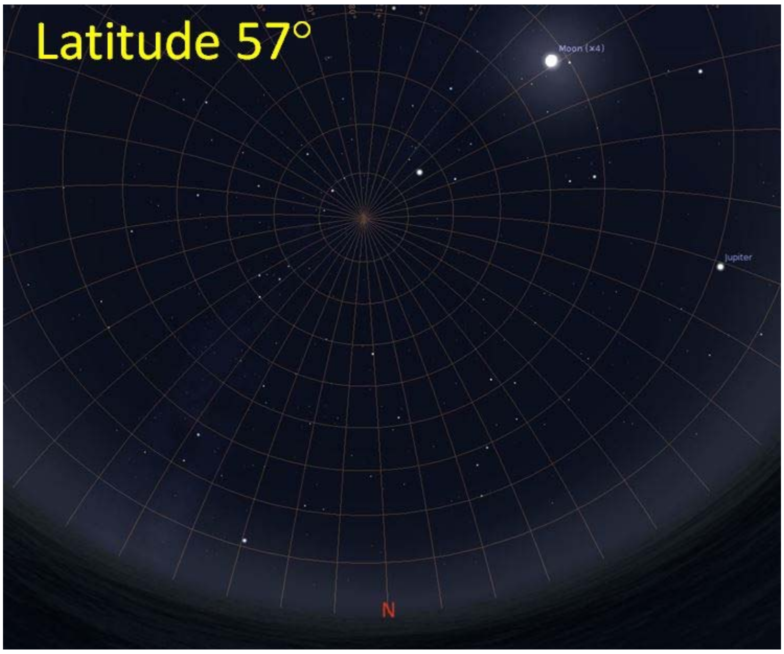
Latitude from Polaris



Finding latitude from Polaris is pretty easy. The latitude is equal to the angle of Polaris above the horizon. It's the same angle all year around. The horizon is not too difficult to find at sea if there is a little background light[4].

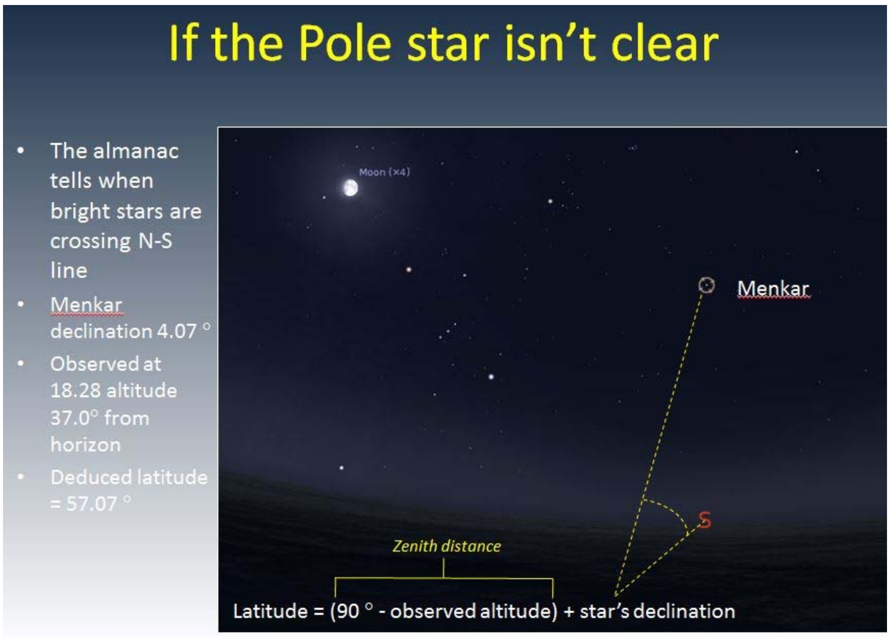
The Canary Islands are a popular destination for a holiday at this time of the year. Clear skies are common and if you locate Polaris on holiday there then you'll see that instead of being 57° above the horizon it's now only halfway up, less than 30°. The Canary Islands are half way to the equator from here.

Latitude 57°N



The screen-shot shows the northern sky tonight from our location with altitude/azimuth mesh superimposed using Stellarium. Look at the altitude lines shown every 10°. Locating Polaris you'll see that it is clearly at 57°. Job done. We're 57° North. If anyone is looking for an idea for the next 'must-have' gadget to invent, then a laser pen that projects a raster of altitude lines seems a good idea. An embedded spirit level will give the horizontal. The energy in each line doesn't need to exceed acceptable safety levels. I'll maybe see you in a couple of years' time on 'Dragon's Den'.

If the Pole star isn't clear



The almanac tells when bright stars cross the N-S line and gives their declination. If you are unsure of the time, then measuring the altitude three times when it's within an hour of due south allows you to find the maximum. The slide shows figures for an observation of Menkar tonight at 18.28. (90° - observed altitude) is the angular distance from the zenith, the direction vertically up.

Latitude from the mid-day sun

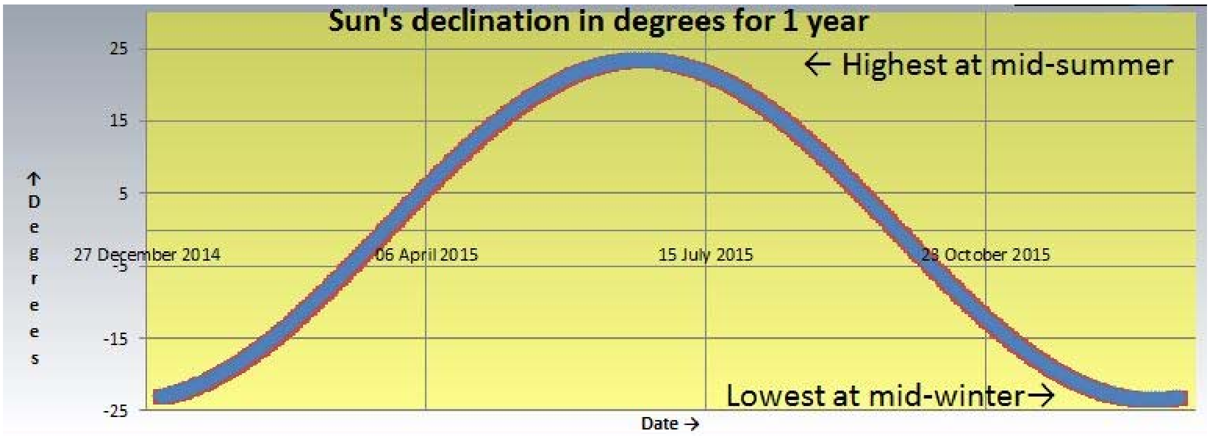
Finding latitude is almost as easy as finding an angle.

If the Sun always circulated over the equator if would be very easy to find your latitude. On the equator, the Sun would go up to 90° (overhead); at latitude 45° the Sun would rise up to

45° and here at latitude 57° the Sun would rise up to 33°. But we all know that the Sun gets higher in the sky as summer approaches and lower as winter approaches. The height of the Sun therefore depends on how high the Sun is above the plane of the equator, a quantity called its *declination*. This varies over the year from +23.5° at midsummer to -25.3° at mid-winter, as seen here. Latitude is therefore given by the angle to the mid-day sun and its declination: *Latitude = (90° - angle to sun) + sun's declination*. See endnote for comment on what happens when you're not sure when midday is[5].

Sun's declination changes with the date

The slide shows a graph of the annual change. It's usual to look up the declination of the Sun

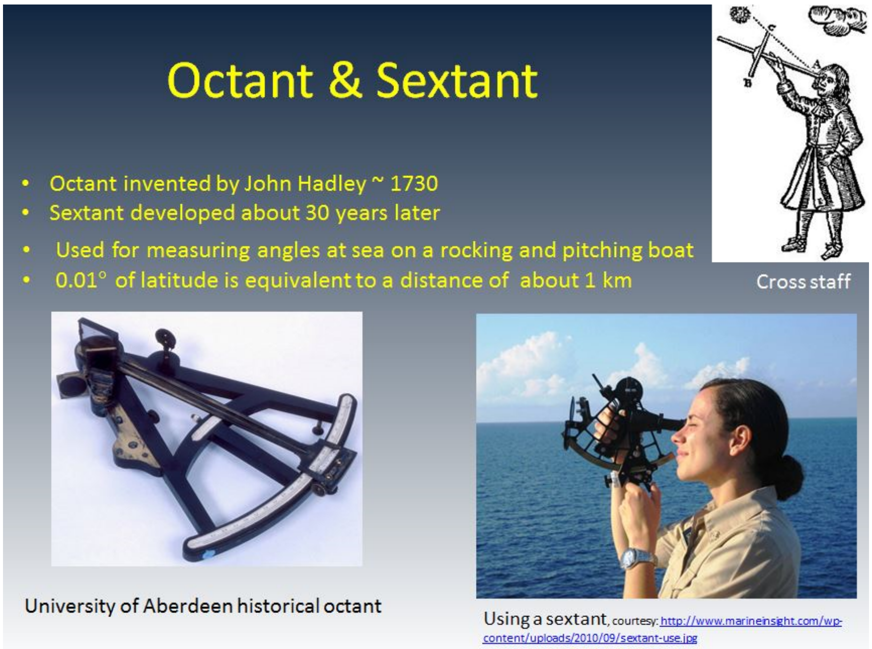


for each day of the year and each hour of the day. In fact the astro-navigator will have a book of tables called the astronomical ephemerides that show not only the declination of the Sun but numerous potentially useful things about the Sun, Moon and stars for every day of the year and every hour of the day. Calculating this accurately and publishing the details well in advance was, and still is, a significant job for one wing of the Admiralty[6]. The Sun's declination is actually easy to calculate if you have to. The flash simulation http://astro.unl.edu/classaction/animations/coordsmotion/eclipticsimulator.html shows what's happening.

The 'bottom line' here is that latitude is defined and found astronomically.

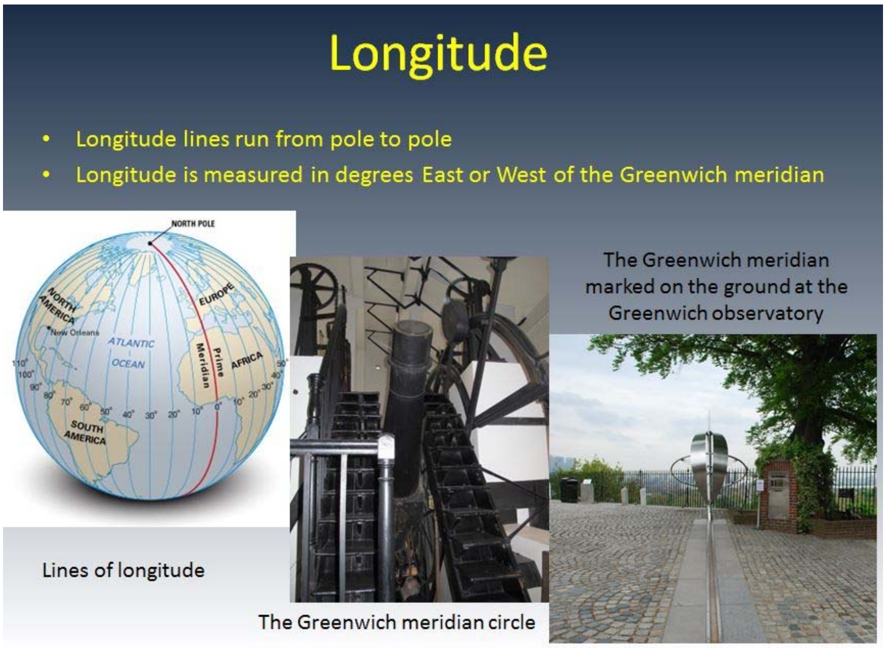
The Octant and the Sextant

Finding latitude at sea means measuring an angle at sea. It's not easily done on a rocking and pitching boat. The cross-staff and back-staff were wooden instruments developed in the 16th century to make this possible but they weren't accurate and were hard to use.



The small sketch on the slide shows a cross staff. Apart from accuracy issues I think there must be a high chance of sorely poking your eye with it on a pitching vessel. The octant was the first really successful instrument for angular measurement, developed around 1730. The octant was called this because its scale occupied one eighth of a circle, though it could measure angles up to 90°. It worked by having a moving mirror that could be turned through a measured angle to bring the star or Sun's reflection down to the horizon. The co-incidence of horizon and reflection isn't changed by the pitching of a vessel. The sextant was a development that allowed angles up to 120° to be measured. In the first instance this was to help longitude determinations from lunar measurements that I'll mention soon but it also helped when the sextant was used to measure horizontal angular distances. I have here a couple of historic instruments, an octant from 1803 and a 19th century sextant. I can show anyone afterwards how they are worked.

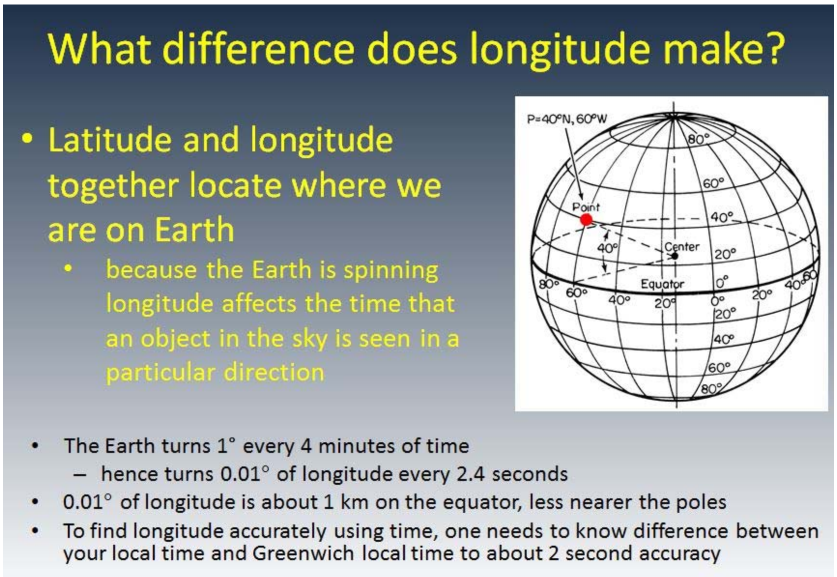
Longitude



Longitude is how far East or West we are. Lines of longitude all converge at the poles. But West or East of what? There is no obvious zero of longitude but in 1884 the International Meridian Conference met in Washington DC and chose the longitude line through the Greenwich meridian telescope as the zero of longitude. The choice of Greenwich reflected the strength of British science and politics at the time. In this building we are 2.10628° West of the Greenwich meridian. The Greenwich meridian is defined astronomically by the line through the axis of the old transit telescope at Greenwich, erected by the then Astronomer Royal, George Airy. My photograph was taken on a visit a couple of years ago. Longitude everywhere is defined astronomically. I'll come to this.

What difference does longitude make?

Put the two ideas of latitude and longitude together and you get lines like graph paper covering the world. The location of every spot has a latitude and longitude. Of course you don't really need to bother about latitude and longitude if all you want to do is go from Aberdeen to Stonehaven. Latitude and longitude are important when making long journeys over uninhabited land or moderate to long journeys at sea. Longitude and time are intimately connected. Longitude determines when the Sun or Moon or a star are in a particular direction. The Earth turns relative to the Sun at 15° per hour or 1° every 4 minutes. To find longitude you need to find the difference in time between your observations and the same observation on the Greenwich meridian. If I phone up my sister-in-law and she tells me that it's 9 am, when my watch says it's 3 pm, I know she's 6 hours behind us and at 15° per hour will be close to latitude 90° West, which she is in St Louis in the States. That's the basis of the idea.



The world is now divided into time-zones about an hour wide so clock time is excessively rough and ready.

Two ways to find longitude

What every navigator needs, then, is to be able to read a clock that shows Greenwich time, wherever they are in the world. For example, suppose we find the Sun is highest in the sky at exactly 2.30 on our GMT clock. Since the world turns 15° per hour, then we are about 37.5° due West of the Greenwich meridian. I say 'about' because we also need a lookup table to find when the Sun exactly crosses the Greenwich meridian. It may be a few minutes early or late by the GMT clock.

Marine chronometer by John Arnold
Photo by JSR

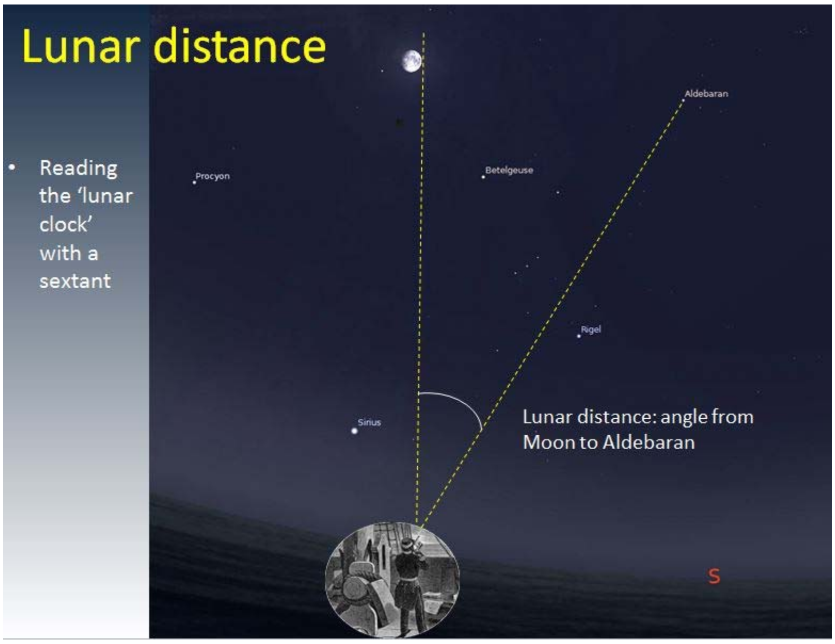
You don't have to wait until midday to find out your longitude. With a GMT clock, if you know your latitude (e.g. based on a Polaris sighting) and have a set of tables that show where the Sun, Moon and bright stars are at any GMT, then you can find your longitude at any time of the day or night by sighting on your chosen object[7].

When Cloudesley-Shovell was sailing and for more than half a century afterwards, the most precise clocks were pendulum clocks. Such clocks wouldn't even keep good time in a paddle boat on the Duthie Park. When James Cook was exploring the Pacific, New Zealand and Australian coasts in 1769/70, one of the most valuable possessions he had on board was the prototype of a new-fangled clock that always kept Greenwich time. His clock worked brilliantly and was the prototype of the marine chronometer. Cook could find his longitude when he wanted to and place his newly discovered lands on a map of the world. Once people could afford the new marine chronometers, this method became the most widely used for determining longitude.

I was reminded when thinking about navigation that I watched the whole of the first series of the TV drama ‘Lost’. The scenario was that a plane flying from Australia to the States crash landed on an unknown island. Throughout the series the participants were saying ’we’re lost, we’re lost, where are we’? If they were anywhere on this world, even in the absence of GPS they could have found out to pretty good accuracy what their latitude and longitude was, for they could measure the shadows of the Sun and they had accurate watches. There was no excuse.

Before people had the technology of the marine chronometer they looked to see if anything could act as a clock in the sky to enable Greenwich time to be known. Two feasible suggestions were the big satellites of Jupiter, and our Moon. Jupiter’s satellites turned out to be too small a target for convenience – about the size of my watch seen 5.5 m away with tiny visible dots that take several days to go around Jupiter[8].

Lunar distance



The Moon is the best bet and its use was promoted for over a century under the title of ‘method of lunar distances’. The Moon is about half a degree in diameter. It moves across the sky by an amount equal to its diameter every 2 minutes. This is almost the same rate as the stars move across the sky but a little slower. So the Moon slips relative to the stars and it is this motion *relative to the stars* that is the clock in the sky. This can be seen readily using Stellarium and advancing the display by one day at a time. The Moon moves about its diameter in an hour. The stars act like the clock dial plate, the Moon like the moving hand. From tables you could find where the Moon was in the sky at any Greenwich time and hence find what Greenwich time it was that corresponded with your observation. Knowing local time you could determine your longitude.


TAKING A LUNAR DISTANCE.

Anyone who could have come up with a method of determining longitude at sea to within 50 km in mid-18th century would have been awarded a prize of £20,000, about as much as the 10 million dollars of today’s X prizes.

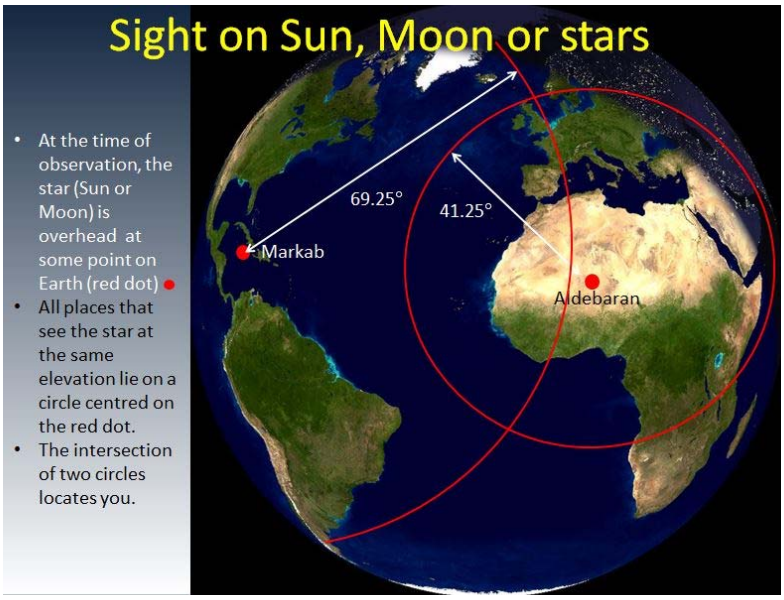
You need your position ***now!***

Finally, maybe the clouds are coming in and you need a fix, as the jargon has it, now.

No problem. You need a clock that gives GMT, a sextant, nautical tables and a horizon. Ideally a pencil and paper too, to record the maths.

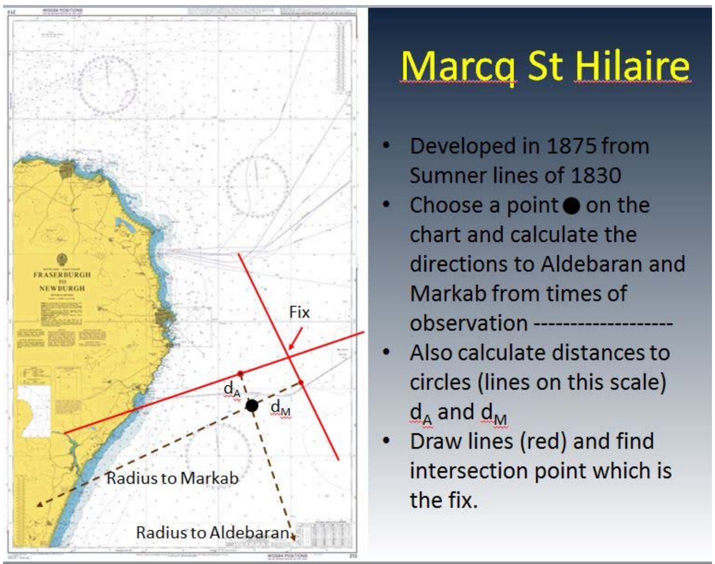
The principle is that sighting two astronomical bodies some distance apart locates where you are. With your sextant you measure the angle of the first body to the horizon and record the time. I've taken the example of a sighting Aldebaran just East of South from out to sea at 7.30 this evening. From the tables you can find where Aldebaran (declination 16.51°, longitude relative to Greenwich 11.85°E) is directly overhead[9], namely somewhere in the Sahara.

Sight on Sun, Moon or stars



This slide will show the idea. I've measured Aldebaran at 48.75° above the horizon and hence 41.25° from the zenith. Observers at all points lying on a circle centred on the Aldebaran point will find the same angle so we must be somewhere on this circle. Now we do the same for Markab over in the West, finding it is 20.75° above the horizon and hence 69.25° from the zenith. Only 2 points on Earth will have the pair of sightings and it should be obvious which of the two I'm at!

Marcq St Hilaire

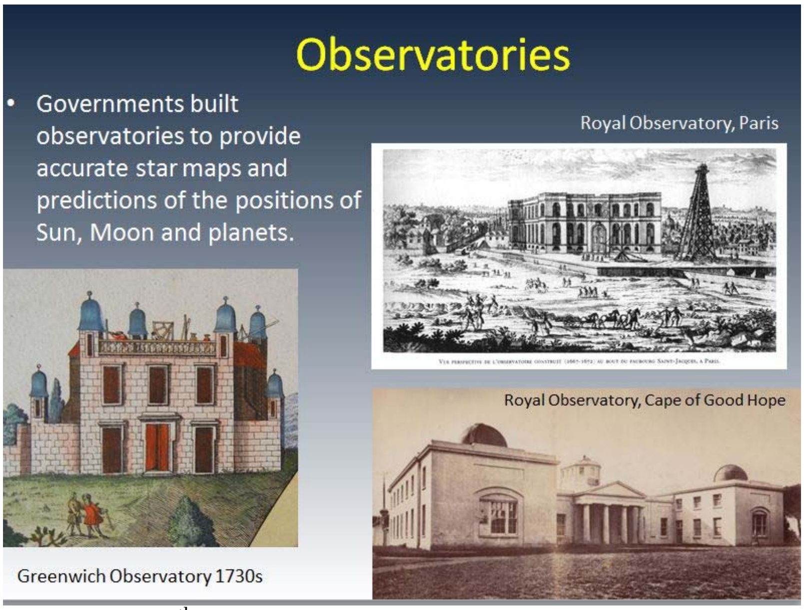


You may have spotted the slight snag that even if you have a globe to draw the circles on, the accuracy in drawing the lines isn't going to locate you at all well. Captain Marcq St Hilaire devised the workaround in 1875. On the scale of any chart you're likely to be using the bit of the circle of interest will be a straight line. Choose any point you like on the chart and some maths that can be done with trigonometric tables shows where on the chart to draw the radius to each star position and where to draw the corresponding line. Do this twice and you've found your fix. I believe this method is still taught in navigation classes.

You may now ask: 'why bother with GPS and circulating satellites today if your position can be found from the circulating stars?' It's partly a matter of the accuracy each technology can deliver. Navigating to the nearest km is good enough for most purposes when you're out of sight of land. Astronavigation can deliver this with the technology of the late 18th century.

GPS can deliver accuracy 1000 times better, to the nearest metre, and that's well beyond astronavigation.

Observatories



Finally, I'll come back to one of my opening comments. For some 250 years from the late 1600s, governments supported astronomy quite generously, not because they wanted to know what stars are and how they work but because astronomy underpinned navigation. Cloudesley Shovell's disaster was just one spur for even greater investment. Our local hero David Gill was Her Majesty's Astronomer at the Cape of Good Hope for the last quarter of the 19th century and he did an enormous amount to promote practical astronomy as well as astronomical science. His post and his observatory were funded by the Admiralty.

Between fixes a change in position was estimated by 'dead reckoning' – basically a calculation from direction, speed and time of travel. An idea of the time of day was therefore useful before the days of clocks and watches. During the day the Sun provided guidance. At night, time could be estimated from the rotation of the stars around Polaris. The direction of the line to the pointer stars was the easiest to use and a mediaeval device called a *nocturnal* allowed time to be measured[10].

To this day the Admiralty still have a Nautical Almanac Office that produce accurate predictions for the positions of Sun, Moon, planets and stars for the coming years. They are part of the UK Hydrographic Office that produce tide tables calculated from this data and charts, all of whose features are ultimately located in latitude and longitude by astronomical means. Practical astronomy is by no means dead and if you're ever lost, or shipwrecked or plane crashed, you can find out where you are to moderate accuracy without GPS.

Since this has been quite a serious talk I'll end on a lighter note. Here is the allegedly true transcript of a radio exchange between the Irish coastguard and a British ship that took place sometime last century.

Irish coastguard. Please divert your course 15 degrees to the south, to avoid collision.

British commander. Recommend you divert your course 15 degrees to the north, to avoid collision.

Irish. Negative. You will have to divert your course 15 degrees to the south to avoid collision.

British. This is the Captain of a British Navy Ship. I say again, divert YOUR course.

Irish. Negative. I say again, you will have to divert YOUR course

British. THIS IS THE LARGEST SHIP IN THE BRITISH FLEET. WE ARE ACCOMPANIED BY 3 DESTROYERS, 3 CRUISERS, AND NUMEROUS SUPPORT SHIPS. I DEMAND THAT YOU CHANGE YOUR COURSE 15 DEGREES TO THE NORTH, OR COUNTERMEASURES WILL BE UNDERTAKEN TO ENSURE THE SAFETY OF THIS FLOTILLA.

Irish. THIS IS A LIGHTHOUSE .... YOUR CALL

"And all I ask is a tall ship and a star to steer her by"

The slide shows some useful URLs.

On-line current nautical almanac for Sun, Moon, planets
- http://reednavigation.com/lunars/nadata_v5.html

Many astronomical concept simulations
- http://astro.unl.edu/animationsLinks.html

Reeds nautical Almanac for 1994
- http://www.reednavigation.com/files/Nautical-Almanac-1994.pdf

Celestial navigation forum
- http://fer3.com/arc/

StarStruck, smart phone astronavigation calculator
- https://play.google.com/store/apps/details?id=com.polyglotz.starstruck&hl=en_GB

One of many explanatory sites
- http://onboardintelligence.com/Default.aspx

StarStruck is a smartphone app demonstrated on the visualiser. It allows you to enter two or more altitude observations (e.g. from your sextant) and find out where you are to an accuracy that depends on the accuracy of your observations, doing all the trigonometric calculations for you. The observations can be Sun, Moon or stars. The results are shown on a map. It also enables you to simulate a sextant recording altitude by using the internal altitude capacity of a smart phone. I've tried this using a cardboard tube to assist alignment. The star or moon is centred through the tube and the phone held against the tube. Even without much practice it seems to work reasonably well.

JSR

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[1] Memo for Stellarium keys: *8* sets time to now; *3* enlarges portion of sky on screen; ';' shows meridian line; *L* advances time at greater rate; *J* slows time; K stops time; + advances by 1 day.

[2] Google map reference 57.167383 N, 2.106538 W

[3] Cloudesley Shovell's tragedy is said to have been the key event that triggered the formation of the Board of Longitude set up to investigate and promote accurate means of determining longitude at sea. Curiously enough, the account of his incident suggests that the fleet thought they were off Ushant on the coast of Brittany, which is 175 km away, more South than East of the Scilly Isle rocks and differs by over 1° of latitude.

[4] The astronomical twilight boundary is defined when as when the Sun is 18° below the horizon.

[5] Knowing local midday accurately isn't that important in that the Sun's altitude changes little in 15 minutes on either side of midday. A good strategy is to take 3 sights spread over an hour on either side of midday (a 2-hour opportunity). Then either graphically or by calculation, find the circle that passes through these observations on an altitude/time plot. The peak of the circle is the mid-day altitude and the time it peaks gives local midday. If times are recorded on a GMT clock then with only the equation of time the longitude can be found too. With sights taken to 1 minute of arc, latitude can be found to close to 0.01° and longitude to about half a minute of time (or about 0.1° of arc). This is good for many circumstances. (My Excel spreadsheet Maxalt.xlsx shows this 3-sight technique working). An alternative way to get the time of maximum is to take a sight before midday and wait until the Sun is at the same height after mid-day. Bisecting the two times gives the clock time at midday and hence the longitude but not an estimate of the latitude without a further sight.

[6] The Admiralty produced the first Nautical Almanac in 1767, though of course information about Sun, Moon and stars was available before that from diverse sources.

[7] Time sight is a general method for determining longitude by celestial observations using a chronometer; these observations are reduced by solving the navigational triangle for meridian angle and require known values for altitude (measured), latitude (known from observation), and declination (from tables). The meridian angle is converted to local hour angle (LHA) and compared with Greenwich hour angle (GHA). The difference between them is the longitude. (For longitude west: GHA = long + LHA). If Dec is the declination of the observed celestial body and H_0 is its observed altitude, the local hour angle is obtained for a known latitude λ from cos(LHA) = $(\sin H_0 - \sin(Dec)*\sin\lambda)/(\cos(Dec)*\cos\lambda)$. The time sight was a complement to the noon sight or latitude by Polaris in order to obtain a fix.

[8] The satellites of Jupiter had been discovered by Galileo and can be seen with a low power telescope. They go around Jupiter with the regularity of the hands of a clock, albeit slow hands. The inner satellite takes 42.5 hours and the next two twice this and 4 times this. The idea was that Greenwich would publish tables showing where they were at given times and by comparing where they are seen from one's ship in mid-Atlantic (say) one could work out the Greenwich time and hence deduce one's longitude. The satellites, though, are pin-pricks of light in a telescope that's hard to hold steady and they hardly seem to move in say 10 minutes. 10 minutes converts to an accuracy in longitude of almost 3° - better than nothing in mid-Atlantic but no good near land

[9] Try http://astro.unl.edu/classaction/animations/coordsmotion/longlat.html.

[10] At night the whirling of the stars around the celestial pole, near enough Polaris, are like the hands of a clock going around the dial. You just need to read the clock. It's not quite so easy as reading an ordinary clock with hands. With an ordinary analogue clock once we learn that 12 O'clock is at the top, the rest becomes pretty easy. Use as a clock hand the line from Polaris to the pointers (see http://astro.unl.edu/classaction/animations/ancientastro/dipperclock.html . At midnight on 31st Jan 2015 (date of talk) our hand is not vertical but nearer 1 O'clock position, as if the clock face has been turned round a bit; on 6th March 2015 our hand is vertical; as days advance our clock face is gradually turning round. 3 months later the clock is on its side and 6 months later it's upside down. With a nocturnal. You look through the centre at Polaris. Set the dial ring to the date, which tells you how much on its side the celestial clock is and then set the pointer to the pointer stars and read the time.