Maritime Navigation – the Scientific Age

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Illustrated notes with selected images from the accompanying PowerPoint presentation

Introduction

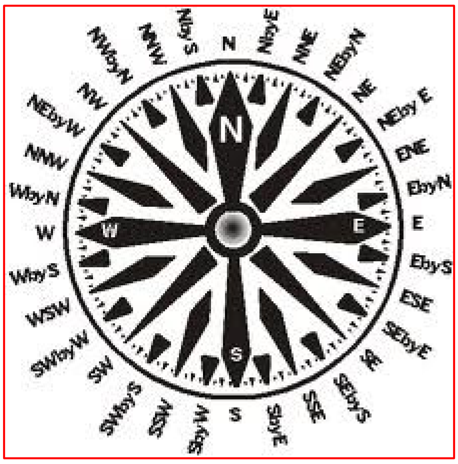
I'm going to talk today about how, over the last few centuries, science has changed navigation almost beyond recognition from a crude skill, by today's standards, possessed by a few to a fine art that can be practised by almost anyone. I'll illustrate the talk with some artefacts from the University's collection of historical scientific instrument collection, and some of my own navigational aids, hopefully making the point that objects give a reality to the story that surpasses PowerPoint pictures.

Navigation – an everyday activity

Navigation – the skill of getting from where you are to where you want to go to. It's something we all do, everyday. I'll start by stating a few obvious facts.

Pre-requisites – you need to know where you are; know where you want to go to; know the direction and distance you need to travel. For most journeys, the path from here to there is usually done in several steps, or sections, and navigational skills are applied 'one step at a time'.

In daily navigation we use a range of personal senses such as memory, eyesight, hearing, the perception of gradient and so on. For longer journeys we are helped by such observations as the position of the Sun in the sky, the orientation of the stars at night, reading maps and using a compass.



Longer journeys introduce the need for navigation aids to supplement our senses. This is especially true at sea. The compass is the obvious aid everyone thinks of and the modern compass owes a lot to science, although primitive compasses were used for navigation in the middle ages. I'll say more about the compass later.

Dead reckoning

Let me begin at the beginning of what I'll call 'the scientific age', namely the past three or four centuries.

Measuring where you were on the open sea during a voyage could be done with little accuracy at all. 17th/ early 18th century navigation was largely carried out by '*dead reckoning*', namely estimating where you have got to by the direction of travel and how far you have travelled, all relative to where you had started from. With dead reckoning the **direction of travel** is the **most important variable of all**.

Suppose you know the coast you are heading for is 650 km away but you steer a course just 5º away from the correct one, very little on a swinging compass, less than half a point on a compass card divided into the traditional 32 sectors, then you will arrive about 60 km away from where you want to get to. That's a lot and if you're closing on a coast the chances are that you won't even recognise where you are when you get to the coast. The slide shows an example of where you'd end up if your course was only 5º off line – very easily done if you had only the navigational aids of 3 centuries ago.

One important concept of dead reckoning is, on a long journey, not to aim for where you want to go to. E.g. if you're sailing across the North Sea towards Amsterdam, the strategy would be to aim to reach the coast North of the entrance to the Amsterdam harbour complex. You may not recognise the coast when you get there but you know you have to follow the coast South for as long as it takes to reach the entrance to the harbour. In reality no-one would have attempted such a direct journey 3 centuries ago. You would have sailed down the coast as far as East Anglia and then made the shortest trip across open water as possible.

With modern navigation aids this technique isn't the one usually employed, for there are well defined shipping lanes you have to be in so you need to know where you are to high precision, but this example illustrates how navigation not only uses different instruments today from in the past but that the navigation techniques themselves can differ from those of the past.

Of course even dead reckoning needs a chart to tell you in which direction you should be going. Accurate charts are an important part of modern navigation. I'll come to them soon.

Knowing where you are

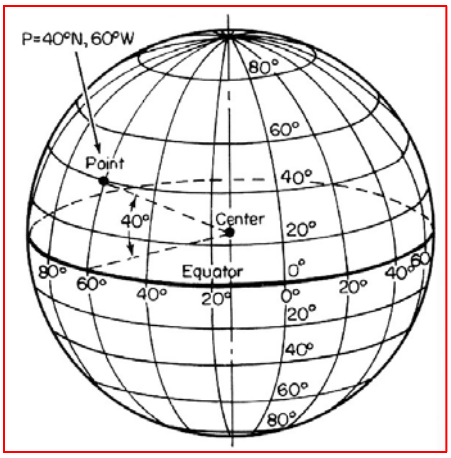
Dead reckoning alone can lead you into big trouble. The result can be that you think you're somewhere you aren't.

There is a often repeated and influential story of dead reckoning leading a fleet into big trouble.

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 holding one of the latest scientific tools to assist marine navigation, a telescope. Cloudesley Shovell had a significant impact on the development of navigation, though that was not his intention. Returning home from an encounter with the French Navy in October 1707 with 5 Royal Navy warships under his command he approached the English Channel in fog, as daylight faded. A young sailor presented himself to the commander, questioning the decision of the navigators 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. His arrogance and navigational misjudgement were quickly revealed, for 4 of his 5 warships were wrecked that foggy night on the rocks of the Scilly Isles; almost 2000 men lost their lives, Cloudesley Shovell amongst them.

This loss, more than any other event, stimulated the Admiralty to persuade parliament to offer a large prize to anyone who could develop better methods of finding position at sea. Position meant latitude and longitude and it was longitude that was the bigger problem. Other maritime nations made similar initiatives at the beginning of the 18th century, their will fuelled by their own maritime disasters.

The slide reminds us what latitude and longitude are exactly. Lines of constant latitude are *small circles*, the equator excepted. Lines of longitude are *great circles*, meaning that their centre is the centre of the Earth.



Accuracy

The problem of finding your location on Earth is all a matter of numbers.

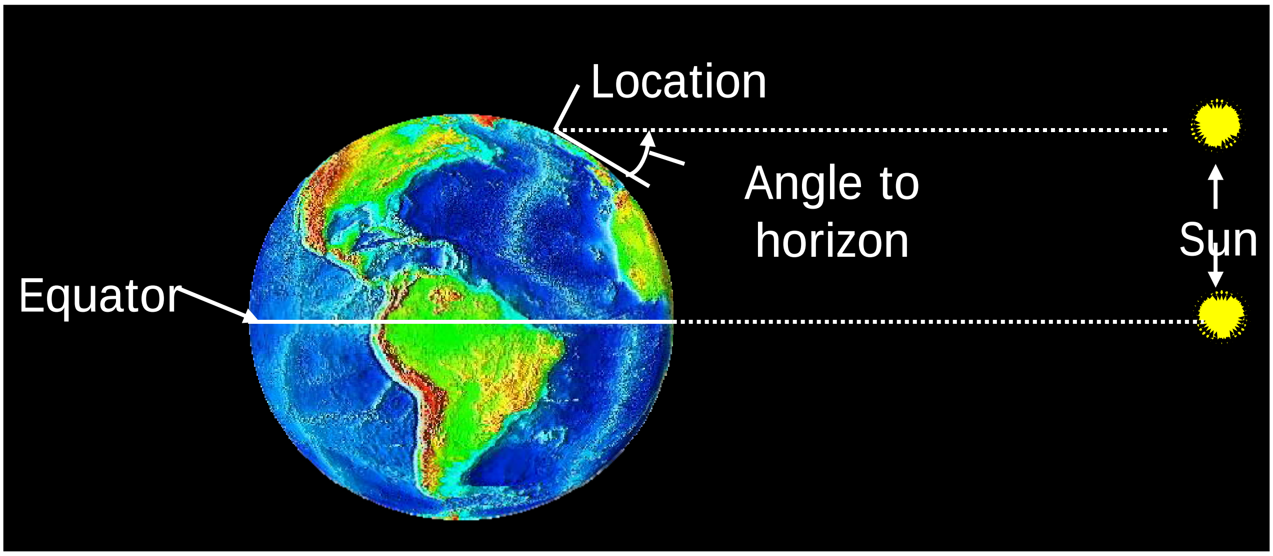
If want to know, your north-south position to within 1 nautical mile (1.85 km) then you need to know your latitude to within 1 arc minute (1' ≡ 1/60th degree). That needs precision instrumentation.

What difference does your longitude make? It makes a difference to when you see the Sun or a given star in a particular direction, such as due South for the Sun or due North for some stars, in the northern hemisphere. I have relatives in St Louis in Missouri. If I were speaking on the phone with my niece and said that it was midday here and the Sun is due south she may well say that it will be another six hours before the Sun is due south with her. The difference in perception is due to our difference in longitude of about 90°. Measuring longitude is therefore intimately connected with measuring time. Lines of longitude converge towards the poles so 1 minute of longitude is only 1 nautical mile on the equator, less nearer the poles. It's about 1 km at the latitude of Aberdeen. However, it takes only 4 seconds for the Earth to turn through 1 minute of longitude so finding longitude accurately means knowing the time to within a second or so. Knowing time to an absolute accuracy of 1 second needs science, in fact quite a lot of it.

Finding latitude

What difference does your latitude make in any case? It makes a difference to how high in the sky the Sun or a given star is seen.

The problem is that to determine one's north/south position to within a nautical mile, the height of the Sun or a star above the sea needs to be found to 1 minute of arc (remember, 1/60th of a degree). That's quite a tall order. The Sun's disk is 30 minutes of arc in diameter. Finding angles to 1 minute of arc needs science.

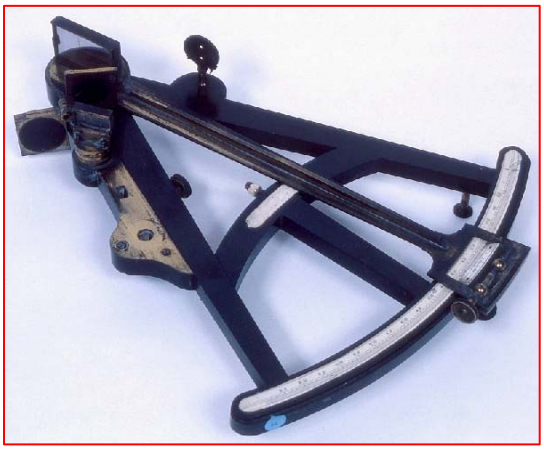


Latitude can be found by the conceptually simple observation of measuring the altitude of the Sun above the true horizon at midday, provided you know what day of the year it is. The day of the year tells you how far the Sun is above or below the equator, provided you have a table with this information in it. The true horizon is supplied by sea level, though it's not that easy to sight the horizon on a modest sized boat tossing around on a rough sea.

[How to find one's latitude had been known about for centuries. If the Sun were above the equator, then the angle of the Sun at midday to the horizon equals (90º - latitude). This happens at the equinoxes. Between the spring and autumn equinox the sun is above the equator, at an angle known as its declination (δ), reaching 23.5º at mid-summer. In general, latitude = (90º - Sun angle to horizon + declination). Since declination changes by 23.5º (= 1410 minutes of arc) in 90 days, its average rate of change is 15.4 minutes of arc per day, or half its diameter. Knowing the declination is essential. This is found from nautical tables, knowing the day in the year that you are measuring the height of the Sun. At night, the altitude of the pole star above the horizon is a direct measure of latitude.]

Enter modern science

The latitude problem was essentially solved in the first half of the 18th century with the invention of the octant by John Hadley in 1731. This device is a combination of optics and



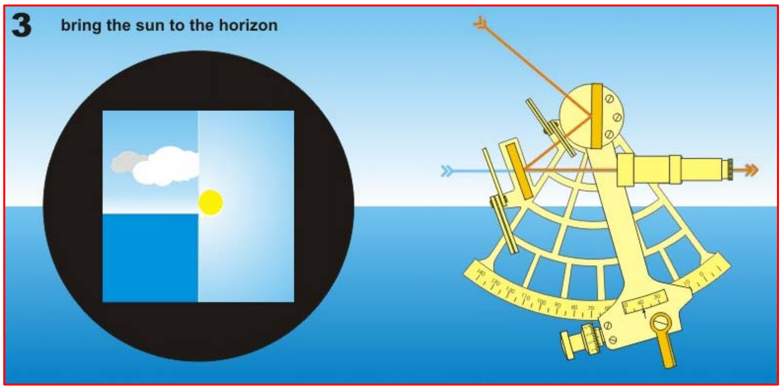
mechanics. It allows one to sight the horizon directly through the clear side of a fixed piece of glass that's half silvered. The other half acts as a mirror and in combination with a second mirror that can be moved allows the image of the Sun, reduced in brightness by one or more dark shades, to be lowered so that the Sun appears to sit on the horizon. The angle by which the mirror has to be moved to achieve this is half the altitude of the Sun. This angle is read from an accurately calibrated scale to a precision of at least 1 minute of arc. In principle, job done.

You can see what some of this means in practice from the octant at the lecture. This example dates from 1803. It needs good craftsmanship, a careful choice of materials and a means of making an accurate scale, which is essentially a high-precision task. The octant can be used to measuring angles up to 90°, which is all you need for altitude measurements.

However, an octant can be used for measuring horizontal angles, too, such as the angle between two headlands. Such angles can be greater than 90°. It can also be used to measure the angle between Sun and Moon, if both are up above the horizon, and quite early in its life the octant morphed into the sextant in the late 1760s. The sextant can measure up angles up to 120°.

Sextant

You can see a real sextant in the lecture. This slide shows 2 images from an animation of using a sextant.



The first picture shows sighting the horizon, both directly and through the mirror. This defines the zero position of the mirror on the scale.

The second picture (right) shows bringing the lower limb of the Sun down to the horizon. The moveable mirror is held in position by either friction or a clamp and the scale read at leisure.

Longitude

Determining longitude needs some sort of reference clock. For example, suppose you leave Greenwich dock with a clock set right so that the Sun reaches its highest point at midday. If you travel 15° west then you will find that the Sun reaches its highest point at 1 pm by this clock and the time difference between midday and 1 pm tells you that you are 15 degrees west, because the Earth rotates 15° in one hour. It may seem odd that Captain Cook while exploring the Far East had an experimental clock that read London time on board. This was nothing to do with patriotism but was his most important navigational tool, one that enabled him to work out his longitude while on the other side of the Earth.

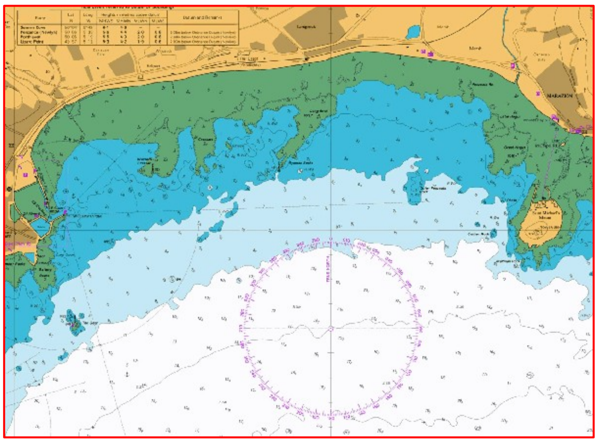
The Moon can be seen against a back-drop of the bright stars and during the 18th century a lot of effort was put in to making tables of where the Moon was in the sky for different hours of the day and days of the year. However, the Moon's orbit is in fact not simple in detail and relative to the stars the Moon goes round once every 27.3 days so the moving hand of the clock that is the Moon is slow, too slow to determine time to within a second or two. One of the main reasons for founding the Greenwich Observatory was to improve the 'method of lunar distances' as it was called, for finding longitude.

The moons of Jupiter discovered by Galileo go around in a time measured in a few days so here there is a clock in the sky with several hands, one for each moon. Galileo both discovered the moons and promoted the telescope for astronomical use so during his life in the first part of the 17th century he was keen on this idea. In practice, Jupiter isn't always in the night sky, the moons are hard to see on a rocking ship and again a few seconds accuracy in reading this clock is too tough a call.

The most accurate clocks on land were pendulum clocks. I hope it's obvious that a pendulum clock isn't going to work on a swaying boat. The story of the development of the marine chronometer by one John Harrison, pretty well a singled handed achievement, over several decades of the 18th century is a story of perseverance, opposition from vested interests and even skulduggery. You can read it in Dava Sobel's paperback [Dava Sobel *Longitude: the True Story of a Lone Genius who solved the Greatest Scientific Problem of his Time,* Penguin Books, London, 1995, ISBN 0-14-025879-5].

The end point of Harrison's work and the Admiralty's recognition of it was the marine chronometer, a precision clock that by the late 18th century could keep track of time to better than a second a day even in the appalling conditions experienced by a sailing ship in poor weather sailing on a long passage from a cold climate to tropical heat. A marine chronometer from the mid 19th century with an interesting story is on display in the Fraser Noble Foyer at the time of writing these notes. See http://www.abdn.ac.uk/~nph126/selected.php?id=10.

Charts



Going out to sea without charts would today be considered foolhardy, indeed negligent. Accurate and detailed charts are a vital part of successful navigation and the probably no-one appreciated that more than British Admiralty, particularly as the British Empire expanded in the 18th and 19th century. There can be few seas that the British Admiralty didn't chart, and chart with precision and thoroughness.

Charts contain:

- coastal topographic features
- islands

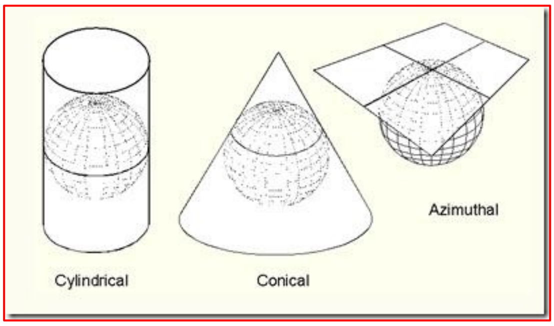
- latitude & longitude
- navigational hazards such as reefs, rocks and wrecks
- navigational aids such as lighthouses and radio beacons
- tidal information
- water depths (soundings)
- compass rose

The examples in the lecture show charts in ‘old style’ with no colours, soundings in feet and fathoms (1 fathom is 6 feet) and fine details of the land obtained from the Ordnance Survey.

Modern charts have depths in metres, simplified land detail, coloured areas to show shallows and deeper water. Yellow for land; green for areas that dry out between the tides, dark blue for water less than 5 m at high water; light blue for water between 5 m and 10 m in depth and white for deeper water. The slide illustrates part of a modern chart of a Cornish bay.

Projections

The world is round and charts are flat and, in short, round into flat doesn’t go. It’s impossible to make a flat map that gets it all right, where equal distances measured on the Earth where-ever you are turn into equal distances on the map **and** directions on the map are the same as directions on the Earth **and** relative areas on the map are all correct, and so on. Something has to give on a map of the Earth or even part of it.

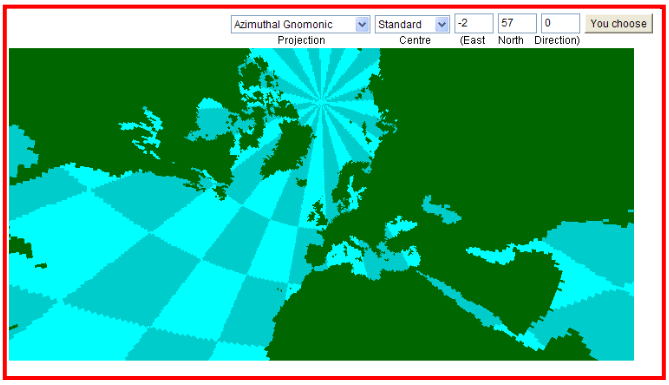


Maps are made by projecting terrestrial features onto a surface that can be rolled out flat. The simplest shapes one can use are an open cylinder, a cone and a plane. One surface feature on Earth gives rise to one point on the map but after that, you can take your choice. There are scores of ways of doing it. You can choose to preserve directions, or distances or local areas, and so on. I’ll mention just three map projections.

Gnomonic projection

Gnomonic projection is done by taking the projection point as the centre of the Earth and drawing an imaginary line through each feature onto the surface of a flat plane, tangent somewhere.

The particular feature of gnomonic charts is that great circles come out as straight lines. Equal distances along a straight line on the map aren’t equal distances on the Earth, but you can’t have everything. The illustration shows the gnomonic mapping centred on Aberdeen.


Azimuthal Gnomonic
Projection
Standard
Centre
-2 (East
57 North
0 Direction)

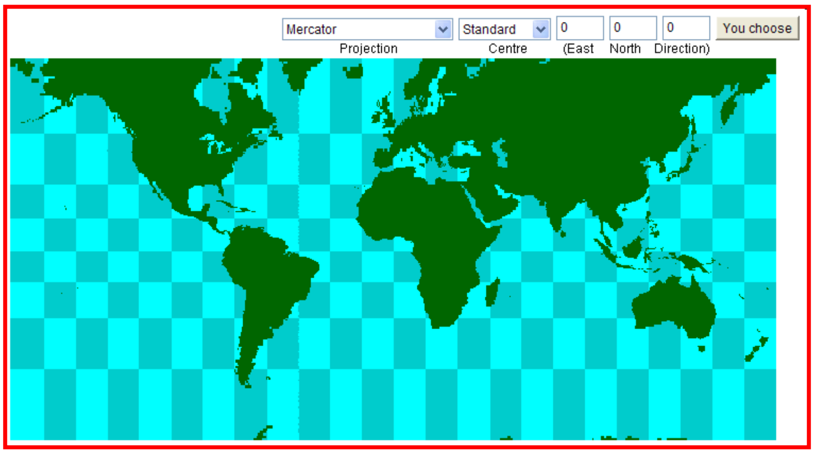
Since great circles between two points represent the shortest distance on the Earth between two points then a large-scale gnomonic chart will show you immediately how to sail the shortest route. For instance the white line I've drawn on the gnomonic chart shows the straight line between the west of Scotland and the Florida peninsular. It passes through Newfoundland and down the East Coast of the America.

Gnomonic charts are also used for small areas, for a small area of the Earth is very close to being flat so to represent it on a flat sheet tangent at one point to the Earth is about the best one can do.

You can try out your own mapping options by running the Java applet at http://www.btinternet.com/~se16/js/mapproj.htm or, for a more comprehensive applet showing different features, try http://www.uff.br/mapprojections/mp_en.html.

Mercator projection

The most common map of the world is a Mercator projection. This preserves directions, not distances, or sizes. It's the projection of the Earth's surface onto a cylinder, which is then cut if necessary, unwrapped and laid flat. The expansion in the direction of the cylinder axis increases in a specific way that preserves directions. A straight line on a Mercator map or chart is a direction of constant compass bearing.


Mercator Standard 0 0 0
Projection Centre (East North Direction)

The white line on the PowerPoint slide shows the constant compass bearing that will get you to Florida. It doesn't go near Newfoundland and until near the end is a long way from the American coast. It will take you on a longer journey than the great circle route.

Orthographic Projection

The orthographic projection shows the land or sea as it would be seen from a long way away. The view of the Earth in orthographic projection centred on Aberdeen really shows the difference in land coverage of the Earth in two hemispheres. Maritime navigation is clearly an essential skill for anyone exploring or trading on the other side of the Earth.

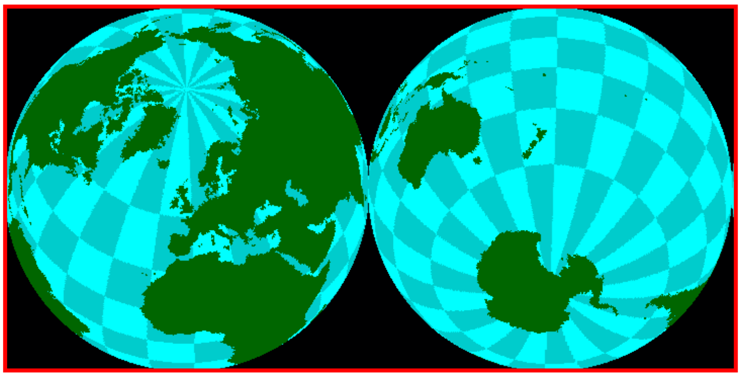
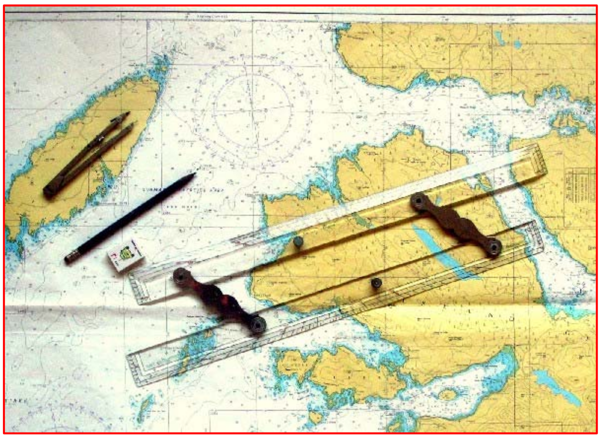


Chart accessories

Charts aren't just for looking at, pretty pictures to be put up on the wall of a cabin or the bar. A chart is a working tool, but a tool that is used with some ancillary tools. Charts are for marking your position, for measuring angles and directions.

With a chart you need a **pencil** to mark lines, usually the intersection of which gives your position. You need a set of **parallel rules** so that the angle of a line can be set on the compass rose and rolled over or stepped over until the line passes through the point on the chart you've measured to. You need **dividers**, or a pair of compasses, because the chart scales are up the side of the chart and a distance to a headland or rocks or whatever has to be transferred from within the chart to the edge. Examples are on display in the lecture.



[These tools would have been amongst those supplied by instrument makers specializing in marine supply. Another specialist instrument on display in the lecture is the **station pointer**. It enables you to quickly locate position on the chart when you know the horizontal angles between 3 features on the coast. Suppose the 3 points you have selected are a hilltop, a lighthouse and a headland. With your sextant or bearing compass you measure the angle between hilltop and lighthouse and then lighthouse and headland. The station pointer consists essentially of a protractor with 3 arms. The arms 1 and 2 are set to the angle between hilltop and lighthouse, and arm 3 is set so that its angle to arm 2 is the same as the second angle measured, between lighthouse and headland. The station pointer is then moved across the chart so that the 3 arms pass over 3 objects sighted. The centre of the pointer is now your location.]

A long distance navigator will need a **nautical almanac** that gives the positions in the sky of Sun, Moon and bright stars throughout the year, and more. Also a set of **nautical tables** that are an aid to working out the mathematics of the spherical geometry needed to reduce general sightings of Sun, Moon or known stars to a position. Nowadays it's much easier with a calculator or laptop but for much of the past 2 centuries trigonometric tables have been used.

Not quite a chart accessory but also needed, particularly for coastal navigation, are **tide tables** that give both the times and heights of high and low water. Predicting tides is another area where detailed scientific knowledge and calculating ability are required. A finally accessory that pretty well every captain or navigator will have these days is a pair of decent **binoculars** to help identify coastal features, or ships that may become a hazard. Sea captains were among the first to utilise the telescope when it was invented in the 17th century and prismatic binoculars, a product of the 19th century, have now replaced the traditional expanding telescope.

The Compass

The compass is the iconic navigational instrument. It is perhaps the last of the analogue measuring devices to be commonly found on almost all boats, for the good reason that it requires no electricity, has few moving parts and can be a crucial directional guide.

Having a compass is a bit like having a nearby signpost pointing north in the water. Unfortunately the signpost isn't quite as useful as a signpost on land. Even in still water, the signpost doesn't point to true north but to magnetic north and the difference in direction between the two can be quite large (over 40 degrees in some parts of the world) and at any one place it varies slowly with time. Secondly, waves on the water cause the signpost to swing around, or the compass needle to drop the simile.

A modern world map showing the variation of the compass over the globe is shown in the lecture. The time change over 4 centuries is also shown as an animation on the slide in the lecture.

The compass swings about a lot on a rocking ship, this particularly applies to old compasses (and sailing ships in particular, that don't have the benefit of modern stabiliser technology). The application of scientific ideas to navigation hasn't just been a matter of replacing old techniques and instruments by different new ones but has also involved overcoming the defects of old instruments. For example, a modern navigational compass is likely mounted in a weather-proof polycarbonate housing (material that didn't exist 200 years ago), on double gimbals to isolate it from the motion of the ship; it is also immersed in a chamber containing oil of a well chosen viscosity that damps residual oscillations (not considered 200 years ago), the magnet is made from alloy that didn't exist 200 years ago, strongly magnetised by electromagnet (that didn't exist 200 years ago), suspended for optimum balance and damping, with sensitivity to only the horizontal component of the Earth's field, and so on. The soft-iron balls (Kelvin's balls) beside a compass binnacle were an effective late 19th century invention of the Scot Lord Kelvin to compensate for the changing magnetism that was induced by the Earth in iron ships. If left uncorrected this magnetism spuriously deflects the compass needle by an amount that depends on the direction the ship is pointing. In addition to all these changes, the modern compass reads in degrees, not compass points.

Distance & speed

Direction and distance have always been the core quantities to measure in navigation. Speed is pretty useful too but you need a clock in one form or another for that.

At sea, distance is measured in *nautical miles* (even in today's metric world) and one nautical mile is the distance due north between two points 1 minute of arc in latitude apart. I.e. there are 60 nautical miles in each degree of latitude, which makes the circumference of the Earth 60×360 nautical miles or 21600 nautical miles. Since the circumference was intended to be 40,000 km from the original definition of the metre then that gives 1.85 km per nautical mile.

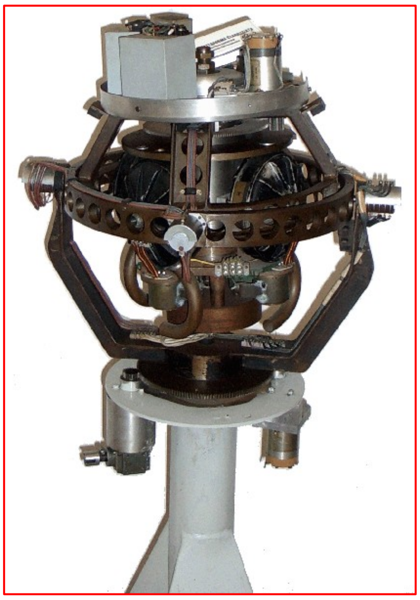
Distance run is measured by a *log*. An instrument on small vessels used to record distance run directly for a long time was one like that shown in the lecture. It consists of a propeller towed behind the boat. As the boat travelled, the propeller spun round and a dial connected to the trailing cord counted the revolutions and was calibrated in nautical miles.

It was simple and reasonably effective but like all devices that use only sensors on the boat, even modern electronic devices, it measures distance travelled through the water, not distance travelled over the chart. Usually the water itself is moving, due to tidal streams or ocean currents, so these need to be known too.

The *log book* was the record of distance run and direction travelled, and other things too like the weather and any issues with the crew or vessel. The name is now generally used for the diary of one's journey or specific activity, maritime or otherwise.

Speed is the ratio of (distance travelled) / (time taken). 1 *knot* is a nautical mile per hour. At sea speeds are measured in knots. The word is based on a traditional method of determining speed, that I'll let you look up.

The Gyro-compass



The gyro compass is a serious piece of kit, which is both its strength – it works well – and its weakness – it costs the user a lot of money.

Gyroscopes and their properties are a 19th century invention and discovery. They are a development of the earlier spinning top. The spinning top will hold an upright orientation until friction gradually reduces its spin. An inclined spinning top will *precess* or rotate about its main axis due to the twist of its weight about the point of support underneath it. However, a body that is effectively supported exactly at its centre of gravity will experience no twist and hence should hold its direction as long as it spins, so long as its centre of gravity doesn't move. Giving the top small electrical impulses to counteract the slight friction of its bearings keeps it going for as long as there is a supply of electricity.

In practice, if such an almost perpetually rotating gyroscope is set up, then the rotation of the Earth has a small effect because it moves the centre of gravity of the top. In a gyro-compass, the mounting constrains the compass to remain with its spinning axis horizontal. In this case the Earth's rotation turns the gyroscope so that its axis swings towards true north. This is the basis of the gyro-compass. Left completely free, the gyroscope would oscillate about true north but in practice there is some controlled damping in the movement, a similar idea to the damping provided by the liquid in a magnetic compass. The compass then aligns itself to true north. To secure good alignment, the spinning disk needs to be quite heavy and it needs to spin very quickly.

The gyro-compass needs precision mechanical construction and electrical control. The first successful ones were made by Elmer Sperry about 100 years ago and he built a very a successful electro-technical company on the basis of the success of the gyro-compass. Gyro-compasses became very common on large vessels.

The gyro compass seeks true north, not magnetic north. It is also not affected by the magnetism of the ship, an issue that plagues a real compass and limits its precision. The example illustrated on the slide is one on display when I visited the works of Officina Galileo, a high-tech navigational company based near Florence in Italy.

Inertial Navigation

The gyro-compass is only a compass, a reference for direction. Inertial navigation takes the electronic basis of navigation even further. The principles involved, though, go back to the basic mechanics of Newton's laws of motion that relate force and acceleration. You may recognise the relationship $F = ma$ between force F and the acceleration a of a mass m.

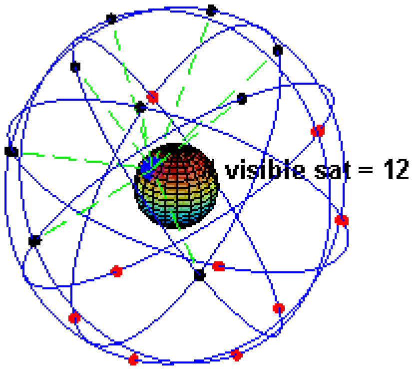
If you stood on a weighing machine in a boat, as the boat was accelerated up a wave the weighing machine display would increase and you could work out the acceleration you were experiencing from the increase in your indicated weight. The reverse happens as the boat drops down the other side of the wave. The up and down motion of the boat doesn't tell you about navigation but if you were standing in a small cabin and had your hands on pressure sensors front and rear, then you could determine forward or backward acceleration which is relevant. An inertial navigation box measures the accelerations of the vessel in 3 dimensions (x, y, z) produced by the engines and the sea. From accelerations, electronics works out the velocities and from the velocities the displacements, i.e. the distances gone in the 3 dimensions. This is done by the application standard mathematics.

An optical technique, which I shan't go into, allows the angular rotation speeds to be measured too, all from within the black-box that is the heart of the modern inertial navigation system. (The devices that do this are called "ring laser gyros"). From the angular rotation speeds, more electronics produces and displays the angular twists of the boat, namely the *pitch* (up and down twist about a sideways axis), the *roll* (sideways twist, about a fore-aft axis) and the *yaw* (slewing about a vertical axis).

You get a lot for your money, but you pay a lot too. Because there is no built-in reference, like true north, nor built-in positions, then starting positions and direction need to be entered. The system then tells you how far you've gone and in what direction relative to its own axes. Major advantages are that there are no moving parts, no friction to be controlled, and negligible 'wear and tear' apart from the occasional failure of electrical components or the lifetime of the lasers (a matter of years). Again, inertial navigation is a solution for large vessels, not small ones. It is also a solution for submersibles, submarines and all underwater craft that can't navigate by GPS because the satellite signals don't penetrate the sea.

GPS and other satellite navigation systems

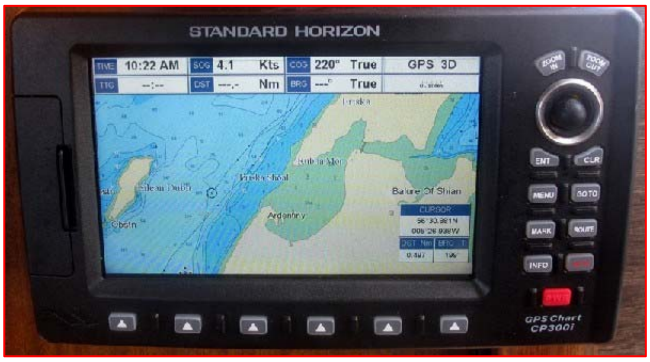
The GPS system most of us now use in boats, cars, etc. was originated by the US Navy and is still run as a military operation. It takes several billion pounds to establish a GPS system. There are 3 aspects to it: the **space side** (satellites to be designed, made and launched, put into their correct orbits, software and hardware to be maintained); the **operations side** (several ground stations that continually monitor and update the satellite operations and signals sent) and the **user side** (the kit that has to be manufactured, sold and put in operation by the user community.



The great advantage of GPS is that the space and operations sides can be lumped as a central cost. Hardware that the user needs can be mass produced for around £100 to the customer (less for cheaper options, more for sophisticated applications). The disadvantage is that the system is ultimately under the control of the central supplier, unlike Gyro-compasses or inertial navigation. This has led to several global positioning systems being developed. The Russian Glonass is fully operational after some years of being out of action. The Chinese are planning a system, though little information about it is in the public domain; the EU is in the middle of developing the only civilian system, called Galileo.

GPS at work

Imagine there is a loudspeaker in each of the front corners of this room and that you each have a microphone and accurate electronic clock. At a precise time the loudspeaker on your left sends out a sharp crack and everyone times the arrival of this sound. Everyone sitting in a circle centred on the loudspeaker will record the same time but those sitting nearer the speaker will record earlier times than those nearer the back, since sound travels at about a third of a km per second. Now the speaker on your right sends out a crack and you time the arrival of the sound again. If you look at the pair of timings you have, no-one in the room will have the same pair of timings as you, and from the known speed of sound you could work out from your times exactly where in the room you were sitting, if I told you exactly where the two speakers were placed. Even more useful, if you moved around in say 30 seconds and then recorded the results again, the difference in the two sets of results would tell you in which direction you had gone and your average speed over the 30 seconds.



GPS works like that, except radio waves are used, not sound. The satellites are high precision clocks in the sky that know where they are at all times. Each satellite sends out a stream of signals specifying accurate time and its location. By timing the signals from 3 satellites with your GPS receiver you could determine where you were in relation to the 3 specified points from where the satellites sent their signals and hence where you were in relation to the Earth's surface. Getting the answer right to within a few metres means timing the satellite signals to about 1/100th of a microsecond (one millionth of a second). It is all a matter of numbers again. Obtaining accurate location is again a problem of precision, timing in this case. As it has turned out, it took less time in the 20th century to develop techniques to measure time intervals to 1/100th of a microsecond than it took John Harrison to develop the marine chronometer accurate to a second or so. However, there was, and is, one big problem with the timing in GPS: the clocks in our user side receivers aren't in fact this precise. So how does the system work?

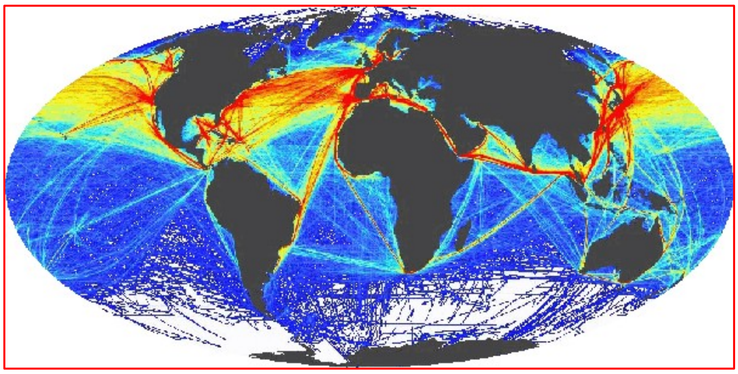
There are many clever details about GPS. One of them is that one can perform the equivalent location method using 4 satellites, not 3, and the extra satellite enables the user side receiver to find the error in its own clock. Timing to 1/100th of a microsecond becomes possible. Locating positions to within a few metres becomes possible. With GPS there is no difference in the difficulty of locating latitude and longitude.

From changing positions with time one obtains speed and direction, the basic necessities of navigation. Job done, in the modern era. The technicalities can be automated to the extent that pretty well anyone can use a GPS receiver and know where they are on Earth, which direction they are moving in, what time it is and more besides. Superimpose the result on an electronic chart, or map and navigation has almost attained its ideal. Anyone can now navigate, to phenomenal precision.

World shipping

One isn't finding one's way these days across almost empty oceans, as this image shows rather well.

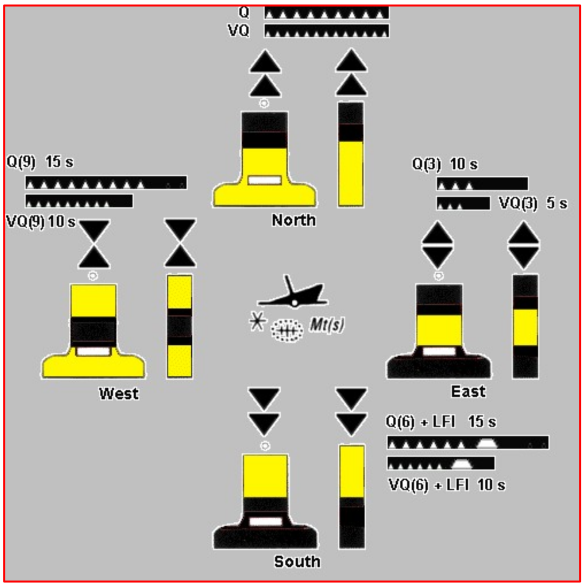
Anyone who has looked at an in-car GPS display in operation will know that it only shows the car you're travelling in. What about the rest of the traffic on the road? I think it's fair to



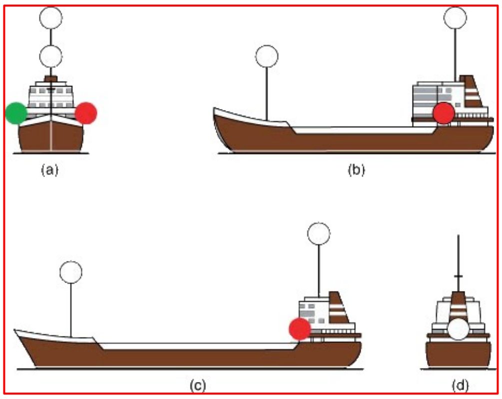
say that if the rest of the traffic were displayed then that would be distracting and really not a lot of help in most circumstances. In shipping though, it would be very useful to see on the chart other boats in the vicinity. This is the purpose of the most modern nautical navigation system called ECDIS (**E**lectronic **C**hart **D**isplay and **I**nformation **S**ystem). It brings together GPS, radar and AIS (**A**utomatic **I**dentification **S**ystem), a system of digital radio signalling which all large vessels must have these days that automatically transmits navigational information and receives it from other ships. The information includes ship identity and the kind of ship it is. Small vessels (less than 300 tonnes at the moment) other than passenger vessels aren't included, so the skipper with ECDIS still needs to keep a visual watch.

Avoiding collisions

It's quite impressive to sit inside the cabin of a boat with no view of the outside looking at the GPS display and tell the helm that they are heading directly for Lismore lighthouse 3 miles in the distance at a speed of 5.1 knots, the island of Kererra is 1.3 miles off the starboard beam, the tide will soon turn in our favour and all seems as it should be. This may seem like navigation heaven but sitting inside looking at the GPS one can't tell if the Mull ferry, as tall as a 7-story building and 10 times as long as one, is bearing down on you at 15 knots. GPS isn't everything in navigation.



Much of this lecture has emphasised the technological applications of scientific understanding that has improved navigation over the centuries. It's important not to forget that navigation has, so far, been a human activity. I wasn't particularly thinking of mankind's ability under unfavourable circumstances to crash their ships into each other, run them onto the rocks, into harbour walls or bridge pillars, and more besides. That's true of course, but there has been a big change in navigational practice over the centuries based on understanding how to avoid such incidents using acquired knowledge of human behaviour. We now have a high degree of international regulation on shipping activities, all designed to make passage safer and avoid collisions. Buoys have recognised shapes, colouring and flashing lights; ships navigation lights are highly prescribed, world wide. Different kinds of ships are obliged to have special distinguishing lights, ships such as aircraft carriers, cable-laying ships, towing ships and so on.



Rigorous rules of the sea, the Prevention of Collision regulations - the Highway Code of the sea – have to be learnt by all licensed navigators. Navigators have to pass a fitness test involving eyesight and colour vision. I remember sitting in a darkened chamber and being presented with different lights, all very small, and being asked to identify what lights were showing. If I'd failed to distinguish a small green (starboard) light from a small red (port) light then instant failure would have resulted.


HMS Astute aground

Of course you can have all the navigational aids that money can buy and years of training but if no-one looks at them, then accidents will happen. As I'm drafting these notes, the £1.2 billion nuclear submarine 'HMS Astute' has just run aground on a shingle bank near the Isle of Skye bridge. It was outside the buoyed channel in waters too shallow, all of which should have been obvious to the navigation officers had they been watching their aids.

On the technological side of collision reduction has been the rise and rise of radar, invented and developed during World War II for the detection of aircraft by Brechin born Robert Watson-Watt. Radar is another science involved in modern navigation.

More technology to explore

I haven't exhausted the technologies that have contributed to navigation over the past four centuries. Lighthouses, for example, may be old in concept but effective lighthouses go back only to the early 19th century. The key to their effectiveness was the development of optics to produce a directed beam visible for many km and a strong, reliable light source. Lighthouses also make exceptionally good landmarks during the day, too. They may be a dying technology that GPS has superseded but smaller beacons and illuminated buoys are still very much with us.

Two other technologies that owe a lot to science are radio direction finding and technology to sound the sea-floor, namely measure its depth and the nature of the bottom. This information has been expected on charts for a century and a half.

Summary – Science in Navigation

The final slide (not shown here) is a summary of topics covered and some related topics that the interested can look into. If you haven't been to Aberdeen's Maritime Museum, then when you're next near the centre of town with some time to spare do look round. Entrance is free and they have a coffee shop.

JSR