CHAPTER 3 - **Position at sea**

[source = http://fr.wikipedia.org/wiki/Navigation]

Navigation techniques were developed by the first sailors to navigate the seas and oceans. The observation of terrestrial magnetism led to the use of the compass which made it possible to hold a course and follow a route. Speed measurements were made possible by the invention of the boat log. These two elements, heading and speed, allow navigation by dead reckoning, which is insufficiently precise over time. Without a terrestrial landmark (out of sight of a coast), the navigators located themselves by observing the stars. The height of a star above the horizon, easily measured with predecessors of the sextant, such as the astrolabe, makes it possible to calculate the latitude. All these techniques were acquired from the 15th century onward. The measurement of longitude, which is deduced from the measurement of time, was only truly possible in the 18th century with the invention of the precise chronometer (or timekeeper) which made it possible to "keep" the time of the meridian of origin.

Thereafter, these means gained in precision and the methods of calculation were refined. At the end of the 19th century, the invention of electricity led to the gyroscopic compass which overcomes the difficulties inherent in terrestrial magnetism. The development of the radio in the first half of the 20th century facilitated the arrival of the first radio navigation systems (principle of radio direction finding). These diversified and developed further, particularly in air navigation where they are important for approaches and landing guidance.

From the end of the 20th century, satellite navigation systems appeared. The basic principle is identical to radio navigation (a passive system where one's position is determined in relation to signals received, often on land; e.g., coastal SYLEDIS, offshore LORAN C), but the beacons are installed on a constellation of satellites in orbit. The availability of low cost receivers allows their installation in even the most basic mobile phones. Satellite systems have, in maritime navigation, supplanted all existing radio navigation systems.

The old techniques based on sextants and chronometers, which do not use electricity, are still relevant because they constitute an emergency means in the event of non-operation (accidental or voluntary) of the electrical positioning systems, or even the only means on traditional pleasure boats.

I Dead reckoning

a) determining direction

There are two types of marine compasses:

fixed on a vertical wall to allow reading from the side,

or placed in a vertical housing to allow reading from above.

They have one or more magnetized needles inside a capsule filled with liquid to slow their movements; the viscosity of the liquid forces the needle (or the graduated sphere) to stop quickly without oscillating on either side of magnetic north. Magnetic needles can also be permanently fixed to a compass dial (wind rose, directional system) which rotates freely around a pivot. Modern compasses also have a device for correcting the magnetic declination to find geographic north directly.

Marine compass with built-in inclinometer and spirit levels

Marine compass with dial (reading from above).

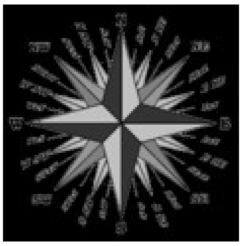
Sailboat compass with sphere (reading from side).

A lubber line, which may be an inscription on the compass cup or a small fixed needle, indicates the longitudinal axis (direction of travel) of the boat relative to the compass dial.

The case is hermetically closed by a glass lid and is fixed to a gimbal suspension. This guarantees that it remains in a horizontal position regardless of the movements of the vessel.

Modern compasses also have a device for correcting the magnetic declination to find geographic north directly.

A wind rose is a figure indicating the cardinal points: north, south, east, west. They often also indicate intermediate orientations, up to 32. In fact, the initial roses did not indicate four directions but eight.



The first "modern" compass rose, oriented towards the north and with 32 points, was drawn by the Portuguese Pedro Reinel in his map of 1504. Before these 32 sectors were called rhumbs (or rhumb or windrose lines) and today are indicated by: North, north-northeast, northeast, east-northeast, east, … west, west-northeast, north-northeast, north-northeast

This kind of magnetic compass could be used on wooden or copper boats but not on metal ships. Other kinds of compasses have been developed:

- the **gyroscopic compass**, based on the gyroscopic effect (discovered by Foucault in 1852), which states that the orientation of the axis of rotation of a spinning wheel or top (free on the 3 axes) corresponds to the axis of rotation of the Earth.

- the **electromagnetic compass** determines the magnetic field from the electrical properties of certain materials subjected to a magnetic field. The four main technologies used in electronic compasses are fluxgate, Hall effect, magnetoresistance, and magnetic induction (dynamo in which a current is induced by the earth's magnetic field when the dynamo is not pointing towards magnetic north; discovered by Dunoyer 1914-18, built by Pioneer (US)).

- Large ships rely on the gyro compass or, more recently, on the satellite compass rather than a magnetic compass for navigation, although the latter must still be installed. The magnetic, gyroscopic, and satellite compasses are frequently associated with a system that automatically keeps a set heading (autopilot) and are integrated into the ship's navigation. Fluxgate electronic compasses are increasingly used on sailboats, even small ones.

Electromagnetic compasses must still be placed far from large metal parts (e.g., motors) affecting the measurement; in any case, the data is transmitted directly to the dashboard and to the ship's on-board computers.

b) measuring distance [source = http://fr.wikipedia.org/wiki/Loch_(bateau)]

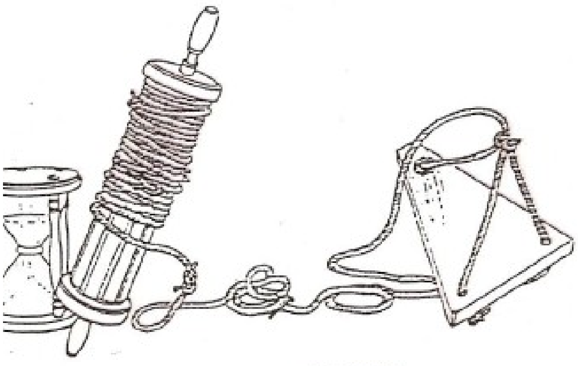
The measurement of speed (V) is essential for navigation. Through integration ($\Delta D=V\times\Delta t$) we can calculate the distance (D) travelled during time t. This integration is automatically performed by modern ship logs (also called "chip log" or simply "log") which contain a distance counter.

The speed measured by a log is the water speed or surface speed (Vs). If the current velocity is known and measurable, the true speed or speed over ground (Vf) can be deduced from Vs using vector analysis.

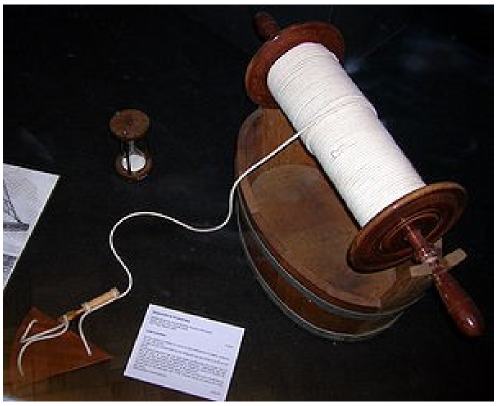
Log comes from the English term for a piece of wood. The piece of wood was thrown off the bow at T=0, the time taken to pass the stern was measured and the speed was calculated as the length of the ship divided by this time.[1]

The first logs consisted of a float (wooden board with an attached weight so it would sink perpendicular to the direction of travel of the ship, acting like a drogue) connected to the log-line which contained knots at regular intervals of 14.40 meters (47 feet and 3 inches); the log was thrown off the stern and the sailor let the log-line run out for a fixed time of 28 seconds while counting the knots that passed over. The length of log-line passing (the number of knots) determined the speed of the ship in knots. Hence, 1 knot = 1 nautical mile per hour or 1,852 meters per 3,600 seconds, or approximately 15 meters in 30 seconds (or precisely 14.4044 meters in 28 seconds).

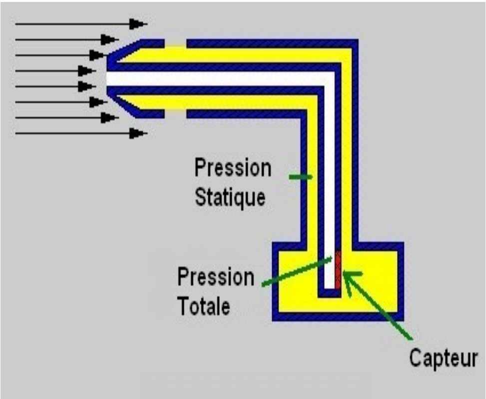
Then appeared the propeller logs: a propeller connected by a line to a counter was launched in the wake; the counter gave simultaneously the speed and the distance covered.



Loch à bateau.



The Pitot tube owes its name to the French physicist Henri Pitot (1695-1771) who in 1732 proposed a "machine for measuring the speed of running water and the wake of vessels". The concept was taken up and improved by Henry Darcy and later by Ludwig Prandtl who used the tube in a pipe to measure local fluid flow speeds (Prandtl tube).



application of Bernoulli's theorem neglecting the z-term to obtain a direct relationship between the speed and the dynamic pressure (pt-ps) that is measured with a pressure sensor or a simple manometer.

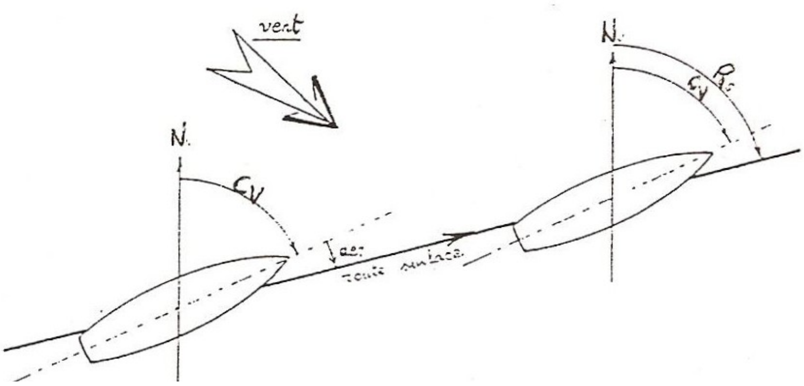
$$\frac{1}{2}\rho v^2 + p_s = 0 + p_t$$

from where

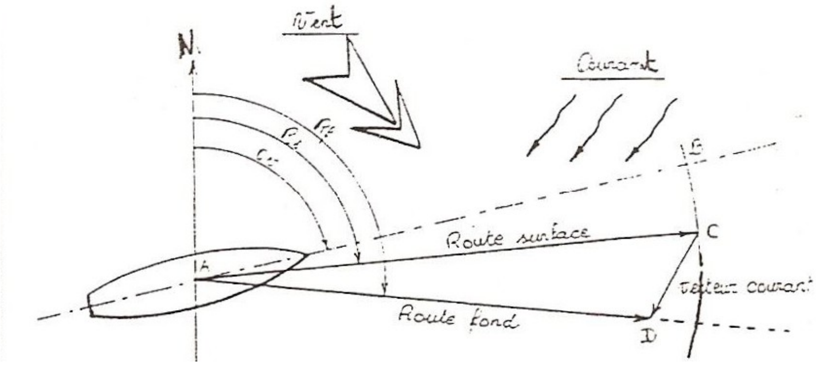
$$v^2 = \frac{2(p_t - p_s)}{\rho}$$

v = velocity, p = pressure in the pipe (ps is the static pressure, pt the total pressure), ρ = density of the fluid

Positioning? Uncertainties regarding the direction and distance travelled



+ uncertainty due to wind effects



+ uncertainty due to current effects

If the quadrilateral of uncertainties is less than the free passage between two dangers, the ship can pass. Otherwise it is necessary to make course corrections when possible (e.g., by passing over a "remarkable probe")

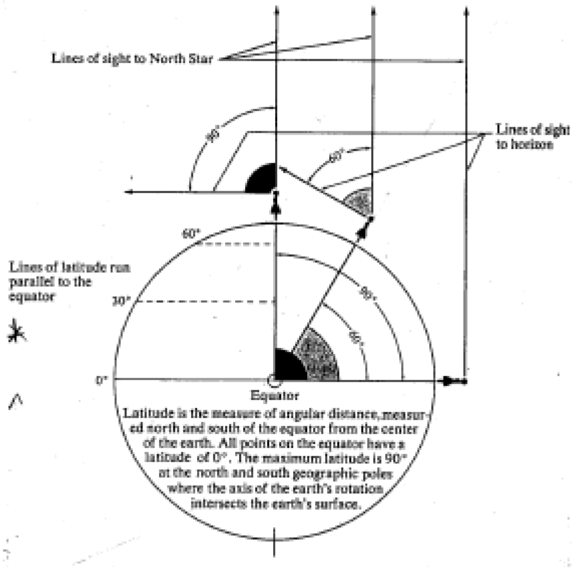
II Navigation by stars

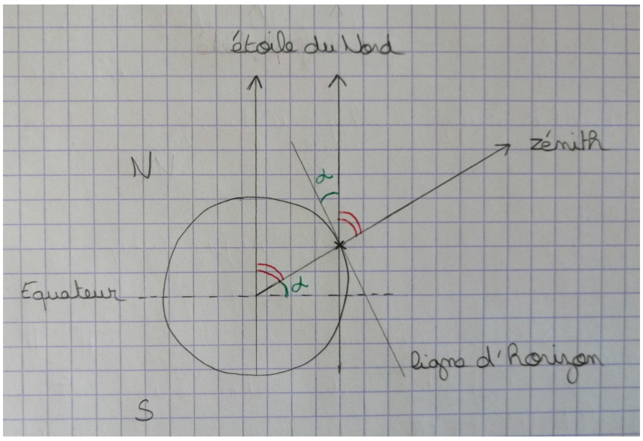
Without a terrestrial landmark (with no line of sight of a coast), navigators find their position by observing the starts. The height of a star above the horizon, easily measured with predecessors of the sextant, such as the astrolabe, makes it possible to calculate the latitude. All these techniques were acquired from the 15th century onward. The measurement of longitude, which is deduced from the measurement of time, was only truly possible in the 18th century with the invention of the precise chronometer (or timekeeper) which made it possible to "keep" the time of the meridian of origin.

A) Latitude was measured in the past, either at noon or via the Pole Star* (Polaris) or North Star. The Pole Star always remains within 1 degree of the North Pole. If a navigator measures the angle of the North Star as 10 degrees from the horizon, then he is at a latitude of approximately 10° N. Angles are measured from the horizon because locating the point directly overhead, the zenith, is difficult. When mist obscures the horizon, navigators use artificial horizons, which are spirit levels reflected in a sextant.

[Definition In astronomy, pole star is a generic term designating a star visible to the naked eye located approximately in alignment with the axis of rotation of a planet, in general the Earth.

Currently, the pole star in the northern hemisphere is Polaris (Alpha Ursae Minoris - α UMi), the brightest star in the constellation Ursa Minor.]





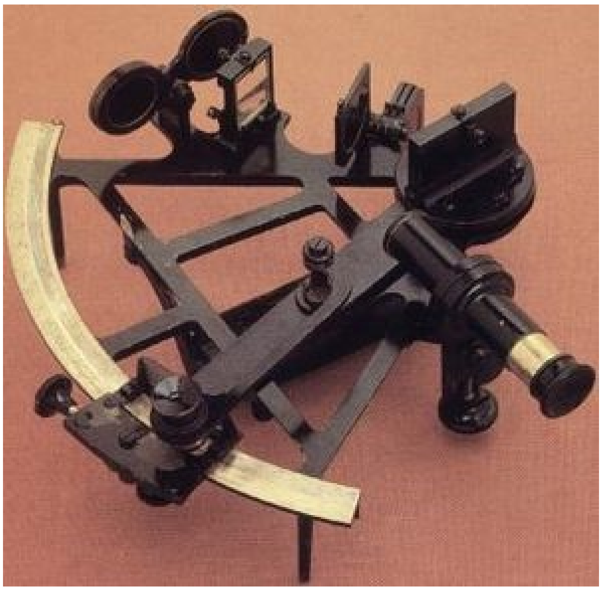
Sum of the angles of a right angle = 90°
Right angle between equatorial plane and pole axis
Right angles between horizon and zenith
A line intersects 2 parallel lines* with the same angle. * = Parallel rays coming from the very distant North Star
(thanks to E. Chevillon, M1, 2021)

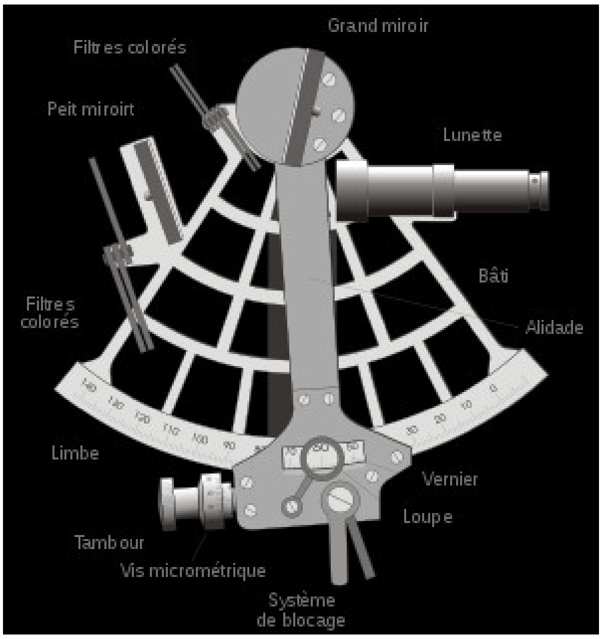
Latitude can also be determined by observing the movement of the stars over time. If the stars rise from the east and move upward (zenith), you are at the equator, but if they drift south, you are north of the equator. The same is true of day-to-day star drift due to the Earth orbiting the Sun; each day a star will drift about one degree. In either case, if the drift can be measured accurately, a simple trigonometric calculation will yield the latitude.

Measuring height using a sextant

The accuracy of measuring tools has evolved over time. A simple and very crude method is to raise your hand with your arm extended. The width of a finger corresponds approximately to 1.5°. The need to have more precise measurement tools led to the development of much more efficient tools like Jacob's staff or the kamal, and in navigation the quadrant, the astrolabe, the octant, and today the sextant, which uses a set of mirrors to measure the height of a star above the horizon with good precision.

While the principle of these measurements was described by the Greeks, it was mostly the Arabs who developed the corresponding instruments (e.g., astrolabe in the 7th century). At the time of John II (1490), this instrumentation had been adopted by the Portuguese. Accuracy was at most 15' which was excellent for the time. The problem of apparent verticality was important. The sextant was invented in 1731 by John Hadley. The reading of a well adjusted sextant allows an accuracy of 0.2'. In theory, an observer can therefore determine their position with an accuracy of 0.2 nautical miles. In practice, navigators obtain an accuracy of the order of 1 or 2 nautical miles (vessel movements, swell, more or less clear horizon, time inaccuracies).





A sight (or measure) consists of bringing the reflected image of the star down to the horizon so it just touches the horizon (hence the pendulum movement of the hand holding the sextant). If the Sun or Moon are used, their lower or upper edges should be brought down so they just touch the horizon. For stars and planets, it is advisable to "rise the horizon" to the vicinity of the star by turning the sextant upside down and then to observe normally [see animation at https://en.wikipedia.org/wiki/Sextant].

B) Longitude

The measurement of longitude based on accurate time keeping only became possible in the 18th century with the invention of the precise chronometer (or timekeeper) which made it possible to "keep" the time of the meridian of origin.

Before that, the determination of longitude posed a real problem because it was based on the measuring the ship's speed and was often highly inaccurate. This posed a problem for trade among other things. So much so that at the beginning of the 18th century the British and Spanish governments offered enormous rewards to the scientist who would find a way to determine longitude accurately. In particular, the Longitude Act passed by the British Parliament in 1714 offered a prize of 20,000 pounds (a considerable sum at the time) to whoever would determine a simple and sure method to allow the determination of the longitude of a ship at sea. This required time keep errors to be below 2s 18 per day (at the time, clocks would drift by at least 1 min per day).

Such a high-precision timekeeper was built by British watchmaker John Harrison* in 1737 who created an enormous chronometer of astonishing precision and stability. Indeed, building such a transportable chronometer is very challenging, not only because of the required precision but also, and above all, because it must be sufficiently stable to operate at sea (such a clock cannot use a pendulum to keep time as the ship is constantly rolling about).

However, it took another 27 years until John Harrison was eventually awarded the prize in 1764 for his fourth prototype, which was much more compact only difted by a few seconds during a voyage lasting two months (error < 4-5 seconds in 10 days), a performance never before achieved.

John Harrison (3 April 1693 – 24 March 1776) was a self-educated English carpenter and clockmaker who invented the marine chronometer, a long-sought-after device for solving the problem of calculating longitude while at sea.

He invented the H1 – H3 clocks and chronometers and finally a pocket watch or timepiece, the H4, which kept time with the necessary accuracy to allow seafarers to precisely determine the longitude of their ship. The calculation consists of comparing the time at the reference meridian (provided by the timepiece) with the local noon (which corresponds to when the sun reaches its maximum altitude).

After many battles with the Board of Longitude, whose members refused to concede that some autodidact would be able to solve this long-standing problem and snatch away the price money stipulated in the Longitude Act, especially using means that did not require any astronomical calculations. Partly thanks to the intervention of King George III, he was finally awarded (part of) the prize money for his marine watch H4.

From the 19th century onward, the watchmaking industry made spectacular progress which enabled the mass production of affordable watches with sufficient precision to calculate longitude easily and quickly.

[adapted from http://fr.wikipedia.org/wiki/John_Harrison_(horloger) and http://fr.wikipedia.org/wiki/Histoire_de_la_mesure_du_temps]

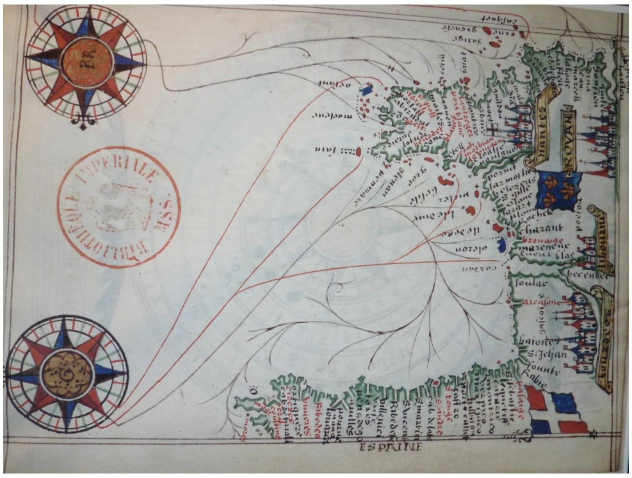
Hence, time keeping became essential in the world's navies as well. More specifically, it meant keeping the local time of the port of departure. Suddenly, following Harrison's invention in the 19th century, helmsmen in the French navy were responsible for winding the ship's watches under pain of death should they forget. In 1908, first attempts were made to transmit a time signal using radio waves (from the Eiffel Tower).

III Nautical charts

Nautical charts (adapted from Wikipedia)

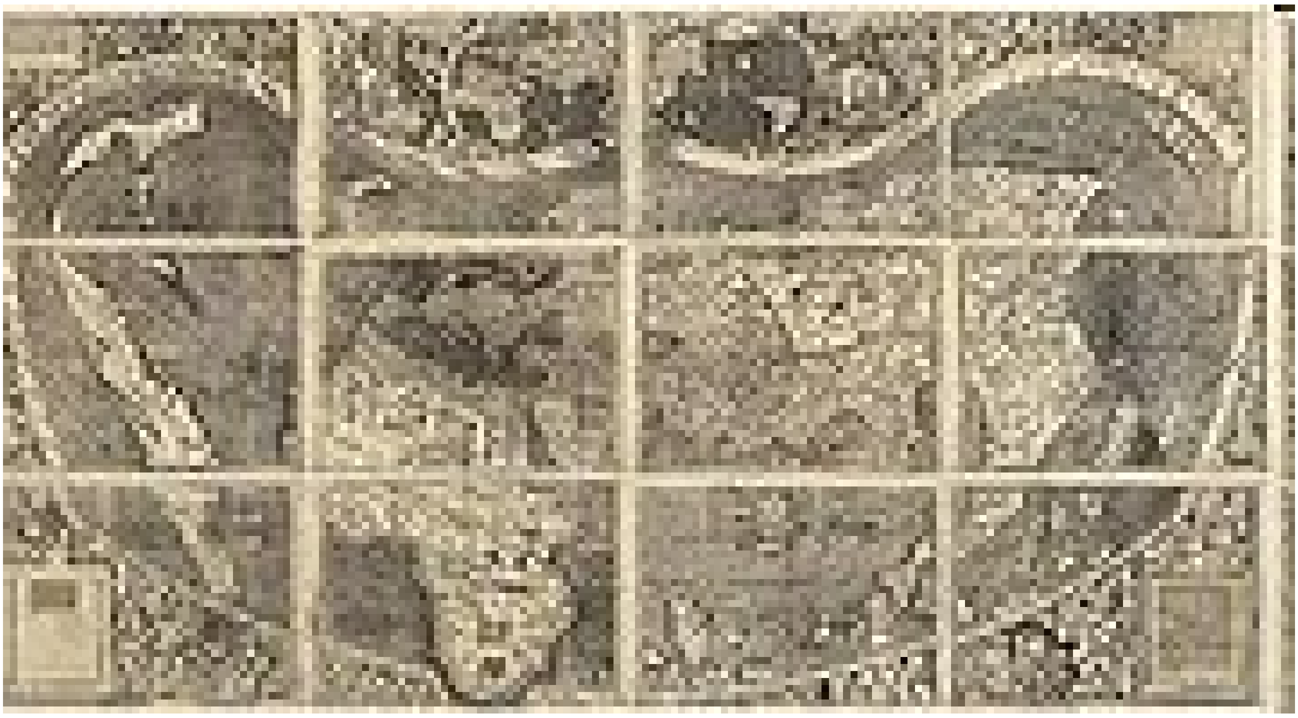
The nautical chart is a particular type of chart reproducing the elements essential to maritime navigation and allows you to locate yourself and navigate. Depending on the scale of the chart, it may show depths of water and heights of land (topographic map), natural features of the seabed, details of the coastline, navigational hazards, locations of natural and human-made aids to navigation, information on tides and currents, local details of the Earth's magnetic field, and human-made structures such as harbours, buildings, and bridges.
Brief history
In Europe, the creation of nautical charts began in the 15th century during the maritime expansion of the European nations of Portugal, Spain and the Netherlands.
Apart from the "global" maps - In the Middle Ages, where the East (representing Jerusalem, symbol of Paradise, of the place to be reached) was placed at the top of the map;

There were the "local" charts - portolan charts for navigation.
A portolan from 1541 >



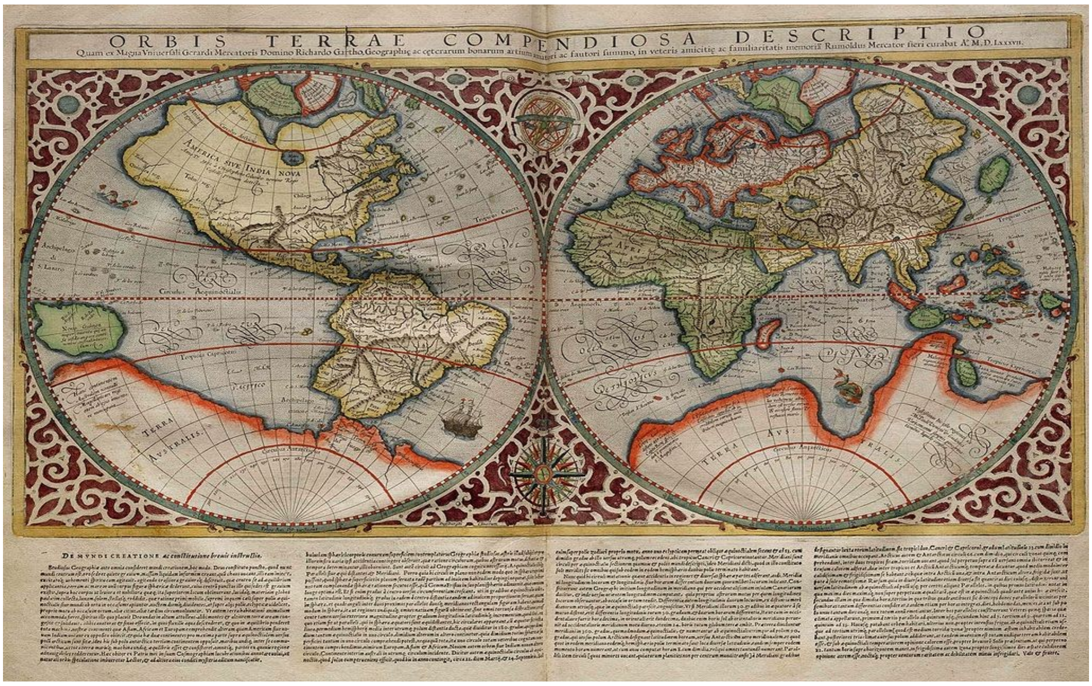
Portolan by Guillaume Brouscon (1548)

The creation of these maps was also one of the essential missions of the explorers of the time, Vasco de Gama, Ferdinand Magellan, Christopher Columbus, etc. Countries guarded this data like their most valuable treasures.



1507 Waldseemüller map containing the new continent and Pacific Ocean (represented 1 century before any European would actually see it). This map was the first to include the Americas (unless the Chinese map by Zheng He from 1400-1430 should turn out to be authentic).

1585 – G. Mercator – cylindrical "Mercator" projection



Planisphere by Rumold Mercator (son of G. Mercator), 1587 having used the projection method of his father

With the appearance of high-performance measuring instruments in the 17th century the first precise maps of the coasts started to appear. The most brilliant cartographers of the time lived in the Netherlands and were supported by the Dutch East India Company.

In 1693, the body of cartographic engineers is created in France (Map depot which will become the Hydrographic Service).

Late 18th century (1790s) – Chabert corrects the map of the Mediterranean

XIX – It was the engineer Charles-François de Beautemps-Beaupré and his team who produced the first nautical chart of the coasts of France between 1816 and 1844.

Today's maps

Nautical charts typically use the Mercator projection but different reference systems:

- An altimetric system to indicate the altitude of land points useful for navigation;

- A depth measurement system to indicate the depth of the water in relation to a reference;

- A coordinate system to locate mapped items in latitude and longitude.

In France, nautical charts are published by SHOM (Service hydrographique et Océanographique de la Marine). [* except the Almanach du marin Breton, published since 1899]

They use as references:

- for altitude: the chart zero of France using the IGN reference system.

- for depth: the chart zero of the nautical charts, which corresponds to the water level of the lowest possible tide (see tides).

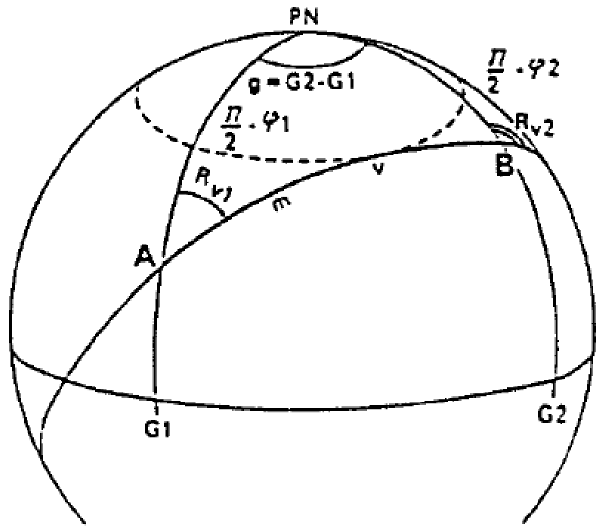
- for coordinates: WGS 84, a system developed for use with GPS.

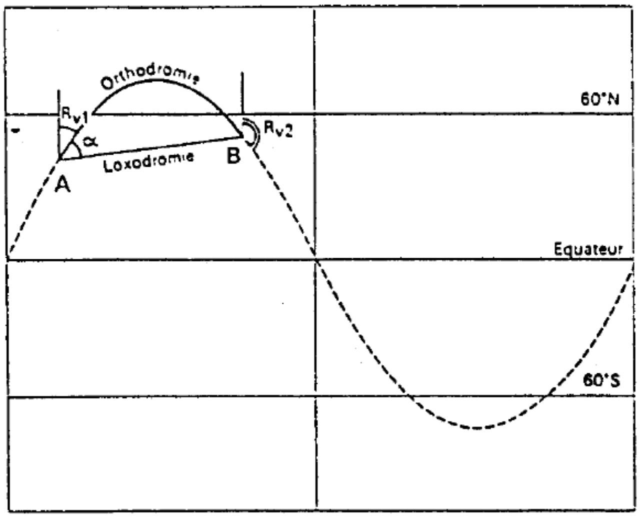
Warning: only maps published after 2001 have been migrated to WGS 84 (World Geodesyc System). Most older maps use the European system 1950 (ED50), to which a correction must be applied.

IV Estimating distances

Orthodromy or “as the crow flies”

Orthodromy refers to the most direct path between two points on a sphere, i.e., along the arc of a great circle which passes through these two points, colloquially referred to "as the crow flies". For navigators, an orthodromic route thus designates the shortest route on the surface of the terrestrial globe between two points.





Here is the result of the calculation of the orthodromy between A (φ_A, G_A) and B (φ_B, G_B) with angles in degrees (φ is the latitude and G the longitude with respect to Greenwich) and distance in nautical miles:

- **orthodromic distance M**:

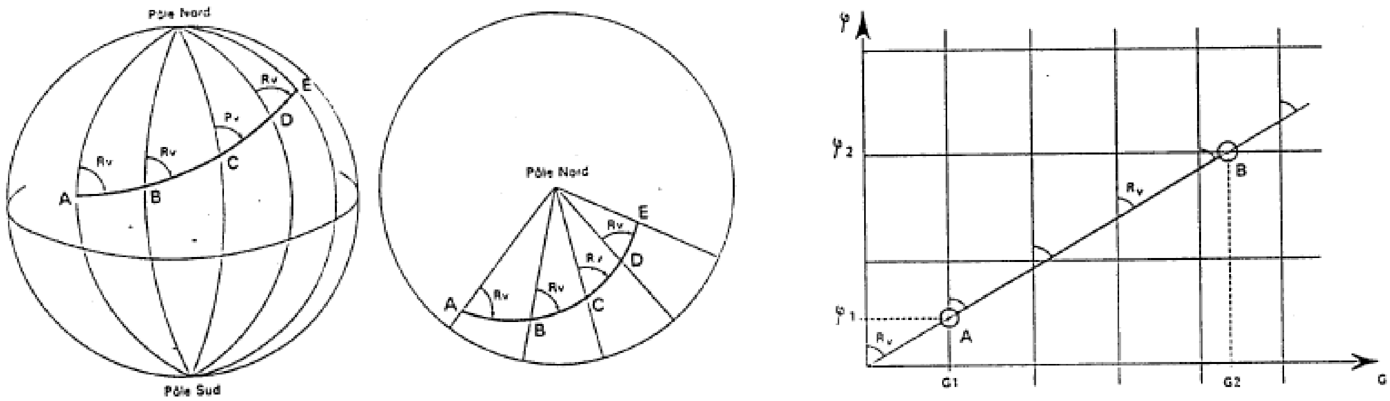
$$M = 60 \arccos[\sin\varphi_A \sin\varphi_B + \cos\varphi_A \cos\varphi_B \cos(G_B - G_A)]$$

in nautical miles (a demonstration here: https://en.wikipedia.org/wiki/Spherical_trigonometry)

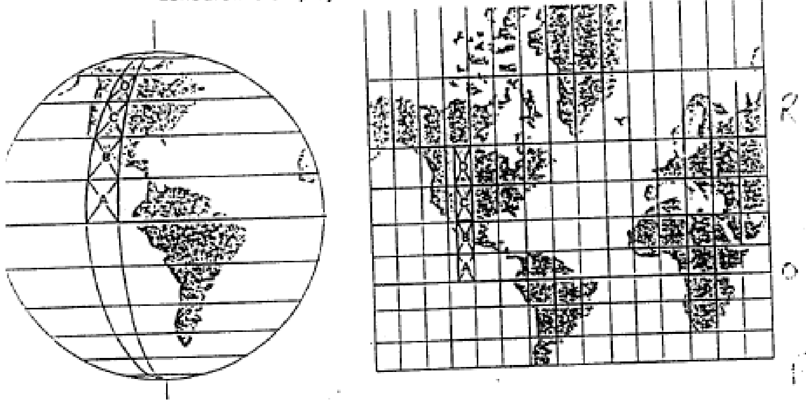
Note: Do not use this formula during practical exercises. Think about doing simple trigonometric calculations. If the cases are too complicated, use the websites making the calculation:
For example for orthodromy: http://www.lacosmo.com/distance.html

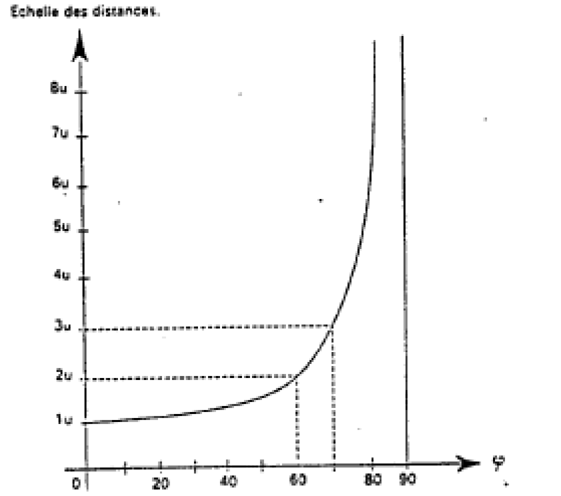
Rhumb line [https://en.wikipedia.org/wiki/Rhumb_line]
A rhumb line, rhumb, or loxodrome is an arc crossing all meridians of longitude at the same angle, that is, a path with constant bearing as measured relative to true north.

On a nautical or aeronautical chart with Mercator projection a rhumb line is represented by a straight line but it does not represent the shortest distance between two points. Indeed the shortest route is called orthodromic route or orthodromy.



-Loxodromie en projection de Mercator.





Variation de l'échelle en fonction de φ.

The route along a rhumb line is a route using constant heading.

Distance along a rhumb line (in nautical miles):

$$loxo(A;B) = 60.\int_0^1 [(lat(B) - lat(A))^2 + long^2 .\cos^2(lat(A) + t.(lat(B) - lat(A))]^{1/2} .dt$$

where long is the difference in longitude between A and B

[see a demonstration at: http://www.univ-lemans.fr/~hainry/articles/loxonavi.html]

V Global Positioning System (GPS)

(https://en.wikipedia.org/wiki/Global_Positioning_System)

The Global Positioning System (GPS), originally Navstar GPS, is a satellite-based radionavigation system owned by the United States government and operated by the United States Space Force. It is one of the global navigation satellite systems (GNSS) that provides geolocation and time information to a GPS receiver anywhere on or near the Earth where there is an unobstructed line of sight to four or more GPS satellites. Obstacles such as mountains and buildings can block the relatively weak GPS signals. It uses the WGS84 system.

The first experimental satellite was launched in 1978, but the full constellation of 24 satellites only became operational in 1995.

Summary

1 - Introduction

The GPS system includes at least 24 satellites orbiting at an altitude of 20,000 km. The GPS receiver calculates its own four-dimensional position in spacetime based on data received from multiple (at least four) GPS satellites. Each satellite carries an accurate record of its position and time, and transmits that data to the receiver. The satellites carry very stable atomic clocks that are synchronized with one another and with ground clocks. By measuring the relative deviations of the clocks, a GPS receiver and know its distance from the four satellites and, by triangulation, locate itself precisely in three dimension.

Regarding accuracy, during the 1990s, GPS quality was degraded by the United States government in a program called "Selective Availability" which was discontinued on May 1, 2000. The GPS service is controlled by the United States government, which can selectively deny access to the system.
For many years, civilians only had access to low accuracy (around 100m). Once selective availability ended, GPS had about a five-meter accuracy. GPS receivers that use the L5 band can have much higher accuracy, pinpointing to within 30 cm, while high-end users (typically engineering and land surveying applications) are able to have accuracy on several of the bandwidth signals to within 2cm, and even sub-millimeter accuracy for long-term measurements. GPS can thus used to locate rolling vehicles, ships, planes, missiles and even satellites moving in low orbit.

It should be noted that in some cases, only 3 satellites may be sufficient. Altitude location (Z axis) is not correct while longitude and latitude (X and Y axis) are still good. We can therefore make do with three satellites when we move on a "flat" surface (ocean, sea). This type of exception is especially useful for positioning flying machines (planes, etc.) which cannot rely on GPS alone anyway, as it is too imprecise to give them their altitude.

2 - Structure

The current GPS consists of three major segments. These are the space segment, a control segment, and a user segment. The U.S. Space Force develops, maintains, and operates the space and control segments. GPS satellites broadcast signals from space, and each GPS receiver uses these signals to calculate its three-dimensional location (latitude, longitude, and altitude) and the current time.

* The space segment (SS) is composed of 24 to 32 satellites, or Space Vehicles (SV), in medium Earth orbit, and also includes the payload adapters to the boosters required to launch them into orbit. The GPS design originally called for 24 SVs, eight each in three approximately circular orbits, but this was modified to six orbital planes with four satellites each. The six orbit planes have approximately 55° inclination (tilt relative to the Earth's equator) and are separated by 60° right ascension of the ascending node (angle along the equator from a reference point to the orbit's

intersection). The orbital period is one-half a sidereal day, i.e., 11 hours and 58 minutes so that the satellites pass over the same locations or almost the same locations every day. The orbits are arranged so that at least six satellites are always within line of sight from everywhere on the Earth's surface.

* The control segment (CS) is composed of a master control station (MCS), an alternative master control station, four dedicated ground antennas, and six dedicated monitor stations. The flight paths of the satellites are tracked by dedicated U.S. Space Force monitoring stations in Hawaii, Kwajalein Atoll, Ascension Island, Diego Garcia, Colorado Springs, Colorado and Cape Canaveral, along with shared NGA monitor stations operated in England, Argentina, Ecuador, Bahrain, Australia and Washington DC. The tracking information is sent to the MCS at Schriever Space Force Base in Colorado. Each GPS satellite receives regular navigational updates that also synchronize the atomic clocks on board the satellites to within a few nanoseconds of each other, and adjust the ephemeris of each satellite's internal orbital model.

* The user segment (US) is composed of hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service, and tens of millions of civil, commercial and scientific users of the Standard Positioning Service.

3 – Basic concept

GPS works by calculating the distance between a GPS receiver and several satellites. The position of the 24 satellites is transmitted regularly to the receiver, which can, thanks to the knowledge of the distance which separates it from the satellites, know its coordinates.

Measuring the receiver's distance from a satellite

The satellites send electromagnetic waves (the civilian signal for free use is at 1575 MHz) which propagate at the speed of light. Knowing the speed of light, we can calculate the distance that separates the satellite from the receiver by knowing the time that the wave took to travel this path.

To measure the time taken by the wave to reach it, the GPS receiver compares the time of transmission (included in the signal) and reception of the transmission wave by the satellite. This distance is called "pseudo range". An error of one millionth of a second causes an error of 300 meters on the position!

Receiver Clock Offset

The difficulty is to synchronize the clocks of the satellites and that of the receiver. The latter typically does not carry an atomic clock like the satellites but must nevertheless operate with a very precise time to be able to calculate the distance between the transmitter and the receiver.

For this reason 4 satellites are necessary to solve the mathematical equation with 4 unknowns which are the position in 3 dimensions plus the offset of the receiver clock with regard to GPS time.

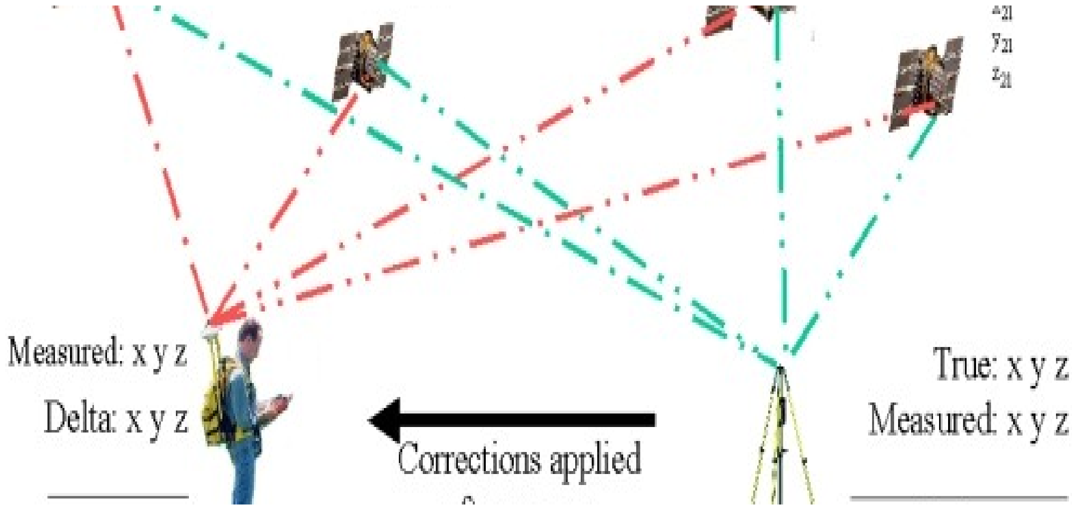
Possible errors and system improvement

Some receivers are able to refine their calculations by using more than 4 satellites (which makes measurements easier) while removing sources that seem unreliable.

The GPS does not work in all situations since the signal emitted by the NAVSTAR satellites is quite weak. By passing through the different layers of the atmosphere the precision is degraded and even the leaves hanging from a tree can absorb part of the signal and therefore affect localization accuracy.

The canyon effect occurring in urban setting can block the direct line of sight to a satellite (because of a high rise building) or, even worse, result in signal echoes as the signals bounce off building surfaces which will not prevent the calculation of a location but will result in a false location.

In addition, there are devices such as the differential GPS (DGPS) which can improve the precision of GPS by reducing the margin of error of the system which increases precision from 10-20 meters to 3-5m.



[source = http://www.ngs.noaa.gov/CORS/CorsPP/WA-SlideShow/index.htm]

Each DGPS uses a network of fixed ground-based reference stations to broadcast the difference between the positions indicated by the GPS satellite system and known fixed positions. These stations broadcast the difference between the measured satellite pseudo-ranges and actual (internally computed) pseudo-ranges, and receiver stations may correct their pseudo-ranges by the same amount. The digital correction signal is typically broadcast locally over ground-based transmitters of shorter range.

The EU has developed EGNOS, which consists of 40 land stations to improve the reliability and precision of GPS data, correcting certain errors.

Converting the obtained information

The 3D positioning thus yields the coordinates of the receiver in space, using a 3D reference frame which has the centre of gravity of the Earth's land masses at its origin. For this data to be usable, the data (X,Y,Z) must be converted to latitude, longitude, and altitude.

The GPS receiver performs this conversion using the geodetic system WGS84 (World Geodetic System 84), the most widely used geodetic system in the world.

This makes the GPS service accessible to trucks, planes, navigators, hikers, surveyors, foresters, motorists, etc.

4 – Inconveniences of GPS

GPS is controlled by the US government. Its signal can be degraded which would result in a significant loss in precision if the US government so desires. This was one of the main arguments put forward for setting up the European Galileo system, which is a civilian system with a precision that is theoretically superior to GPS.

5 – Alternative systems

- GLONASS (in Russian: ГЛОНАСС, acronym for глобальная навигационная спутниковая система, globalnaïa navigatsionnaïa spoutnikovaïa sistéma, or “global satellite navigation system”) is a satellite positioning system of Soviet origin and managed by the army of the Russian Federation. The space segment uses twenty-four satellites circulating in a medium orbit. The system became operational in 1996, but the financial and economic crisis that hit Russia at the end of the 1990s no longer allowed it to maintain a sufficient number of satellites. The full service was only restored in 2010 and became operational again at the end of 2011;
- Beidou (also known as COMPASS, BeiDou Navigation Satellite System, or BDS) is a Chinese satellite-based navigation and positioning system in the process of being deployed and is expected to become fully operational in 2020. An initial version of Beidou comprising three satellites and dubbed Beidou-1 began to be deployed in 2000 and was declared operational in 2003. This regional system made it possible to determine its position only in China and the surrounding areas with an accuracy of about 100 meters. A second generation of the system, Beidou-2, announced in 2006 should provide worldwide coverage by the end of its deployment in 2020. This is ensured by three types of satellites: 5 satellites in geostationary orbit, three in inclined geosynchronous orbit (55°), and 27 in medium orbit. Beidou-2 has been operational since late 2012 with coverage including China and surrounding countries. Fifteen satellites were in orbit by early 2015. The performance of Beidou-2 will eventually be comparable to the three other operational global systems (GPS, GLONASS, and Galileo).
- India also has its positioning system: the IRNSS (Indian Regional Navigation Satellite System) whose deployment was theoretically completed at the end of 2016. Its coverage is regional: the receivers can operate in India and on its outskirts up to a distance of 1,500 to 2,000 km from its borders. Terminals in the basic service provide a position with an accuracy of 20 meters. The IRNSS system is compatible with the GPS and Galileo systems.
- Galileo is a satellite positioning system (radio navigation) developed by the European Union within the framework of the eponymous program and includes a space segment whose deployment should be completed around 2020. Like the American GPS, Russian

GLONASS and Chinese Beidou systems, it allows a user equipped with a reception terminal to obtain their position. The expected precision for the basic free service is 4 m horizontally and 8 m in altitude. A higher level of quality will be provided within the framework of paid services offered to professionals.

The Galileo space segment will eventually consist of 30 satellites, including six spares. Each satellite weighs approximately 700 kg and circulates in a medium orbit (23,222 kilometres) in three distinct orbital planes with an inclination of 56°. These satellites emit their own signal and retransmit a navigation signal provided by the Galileo control segment. The latter consists of two stations also responsible for monitoring the orbit and the state of the satellites.

The Galileo project was launched on May 26, 2003 with the signing of an agreement between the European Union and the European Space Agency responsible for the space segment. One of the main motivations of the project was to end Europe's dependence on the American GPS. Unlike GPS, Galileo is purely civilian. The project had to overcome opposition by certain EU members and by some US decision-makers as well as the difficulties of financing (the final cost is estimated at five billion euros). Galileo tests began at the end of 2005 with the launches of the precursor satellites Giove-A and Giove-B in December 2005 and April 2008. The first satellites in operational configuration (FOC) were launched in August 2014. As of April 2, 2019, 26 satellites have been launched, of which 22 are operational. The first Galileo services have been running since December 15, 2016. Maximum precision was reached in 2019, with 24 of the 30 satellites operational, and Galileo should be fully deployed in 2020.

- The Japanese space agency, JAXA, has developed the Quasi-Zenith Satellite System or QZSS, also nicknamed Michibiki, which is a regional satellite positioning system complementary to the GPS system. The QZSS system uses the signal emitted by three satellites in geostationary and geosynchronous orbits over Japan. GPS receivers that pick up the signal from these three satellites can deliver an increased accuracy. In addition, signal losses are significantly reduced in mountainous areas and in urban areas (where signals can experience echo or blocking by buildings). The satellites are in an elliptical geosynchronous orbit which allows them to be visible from Japan at a significant elevation over part of their orbit. Three satellites circulate in the same orbit and one satellite is in geostationary orbit. In April 2016, the Japanese government approved the project to launch three more satellites in 2023 to improve the quality of service.

APPENDIX

1) Explanation of the differences between Galileo et EGNOS

What is GNSS?

The term ‘global navigation satellite system’ (GNSS) refers to a constellation of satellites providing signals from space transmitting positioning and timing data. By definition, a GNSS provides global coverage.

GNSS receivers determine location by using the timing and positioning data encoded in the signals from space. The USA’s NAVSTAR Global Positioning System (GPS) and Russia’s Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) are examples of GNSS.

Europe is in the process of launching its own independent GNSS, Galileo. Since 2011, four Galileo satellites have been launched and used as part of the In-Orbit Validation phase, allowing the first autonomous position fix to be calculated based on Galileo-only signals in March 2013. The Commission aims to have the full constellation of 30 Galileo satellites (which includes six in-orbit active spares) in operation before the end of this decade." Galileo will be interoperable with GPS and GLONASS. This interoperability will allow manufacturers to develop terminals that work with Galileo, GPS and GLONASS.

What is SBAS?

Satellite-based augmentation systems (SBAS) such as EGNOS* are regional contributions to improve the performance of GNSS systems.

The performance of a satellite navigation system is assessed according to four criteria:

- Accuracy refers to the difference between the measured and the real position, speed or time of the receiver.
- Integrity refers to a system’s capacity to provide confidence thresholds as well as alarms in the event that anomalies occur in the positioning data.
- Continuity refers to a navigation system’s ability to function without interruption.
- Availability refers to the percentage of time during which the signal fulfils the accuracy, integrity and continuity criteria.

EGNOS improves the accuracy and the reliability of GPS information by correcting signal measurement errors and by providing information about the integrity of its signals.

* Example: EGNOS

The European Geostationary Navigation Overlay Service (EGNOS), Europe’s first venture into satellite navigation, improves the open public service offered by the USA’s Global Positioning System (GPS).

EGNOS makes GPS suitable for safety critical applications such as flying aircraft or navigating ships through narrow channels (see the EGNOS video for more information).

Known as a satellite-based augmentation system (SBAS), EGNOS provides both correction and integrity information about the GPS system, delivering opportunities for Europeans to use the more accurate positioning data for improving existing services or developing a wide range of new services.

2) Another widely used geolocation system, although it does not reach the degree of precision of the previous ones, is mobile telephony by identifying the nearest antenna(s). Its accuracy remains directly dependent on the antenna mesh density and is only a few kilometers at most in rural areas.

Press clippings:

International Herald Tribune
Dec 9, 2008

TECHNOLOGY & MEDIA WITH REUTERS

Life, liberty and GPS: Advances have limits

New technology not always welcome

By Noam Cohen

Among international outrages, depriving citizens of personalized maps seems far down on the list.

Still, that was the condition put on the introduction of iPhone 3G in Egypt. The government demanded that Apple disable the phone's global-positioning system, arguing that GPS was a military prerogative.

The company apparently complied, most likely taking a cue from the telecommunication companies that sell the phone there, said Ahmed Gabr, who runs a blog in Egypt, gadgets-arabia.com, and wrote about the iPhone's release there. "The point is that using a GPS unit you can get accurate coordinates of any place, and thus military bases and so on could be easily tagged," he wrote in an e-mail message.

I met Gabr last summer in Alexandria, Egypt, at the worldwide conference for Wikipedia. He was typical of the young Egyptians in attendance — hungry for new technology, hopeful about what it would mean for their country.

As much as any country, however, Egypt illustrates the push-me-pull-you nature of technology under an oppressive government.

Young people flock to Facebook, in a way I never could have imagined. In the largest Arab country in the world, Facebook was a way for the educated elite to reach out to one another and to those who had left the country for an even more elite education.

Andrew Bossone, an American in Cairo who writes about technology, said that despite its expense, the iPhone in Egypt was "really popular — everyone knows the iPhone." In addition to editing a technology magazine, he teaches at the American University in Cairo. "One of my students who comes from a wealthy family has the iPhone, and one of my designers, who is not rich, bought it on credit," he said.

Bossone said he thought the government would relent on issues like GPS because it would side with business even at the expense of security concerns.

"The economy is itself a security issue," he said. "The slower the economy grows, the more people become discontented, and that is a security issue."

But thus far, each time technology has promised to help introduce democracy to the country, the young peoples' hopes have been dashed. A movement for political reform that used Facebook to organize protests over the spring was shut down. The authorities cracked down, jailing many of its organizers. In the last few weeks, a blogger affiliated with the radical group the Muslim Brotherhood was arrested for his writings, according to the Arabic Network for Human Rights. Another blogger is being held in a military camp, the group says.

It is enough to make one wonder if new technologies — the personal computer, the Web, the smartphone — will help set us free or merely give us that illusion.

Apple modified its phone without any public acknowledgment. In a series of e-mail exchanges and brief telephone conversations, an Apple spokeswoman detailed the success of the iPhone rollout around the world — a total of 13 million phones shipped since it was introduced in June 2007, and more than 200 million applications downloaded.

But she did not address how the iPhone came to be disabled or whether Apple had a policy it followed in modifying its products to meet the demands of governments worldwide.

This issue remains acutely relevant as Apple negotiates the introduction of the iPhone to China, whose estimated 500 million users make it the big kahuna of cellphone markets. Some reports say that in addition to issues like revenue sharing, there has been talk about modifying the phone so as not to use the 3G network or offer Wi-Fi capability.

Gabr described in his e-mail message what he considered to be the faulty rationale for the policy in Egypt.

"From a technical point of view, this is totally pointless because Google Maps works flawlessly here — you can even get a clear snap (with accurate coordinates) of places you're not supposed to see."

As an aside, he said that months ago he "bought an American iPhone 3G via eBay" with full functionality. "Cheaper, earlier and without compromise," he wrote, signing his note with a self-satisfied smiley-face emoticon.

I must admit, I didn't exactly think that the right to GPS was one of the basic freedoms. But Arvind Ganesan, director of the business and human rights program of Human Rights Watch, placed the issue in a larger context.

First, he described freedom of information as part of the broader, better known, freedom of expression. Transparency about the government's budget, for example, can be crucial to eliminating corruption and instituting democratic reforms.

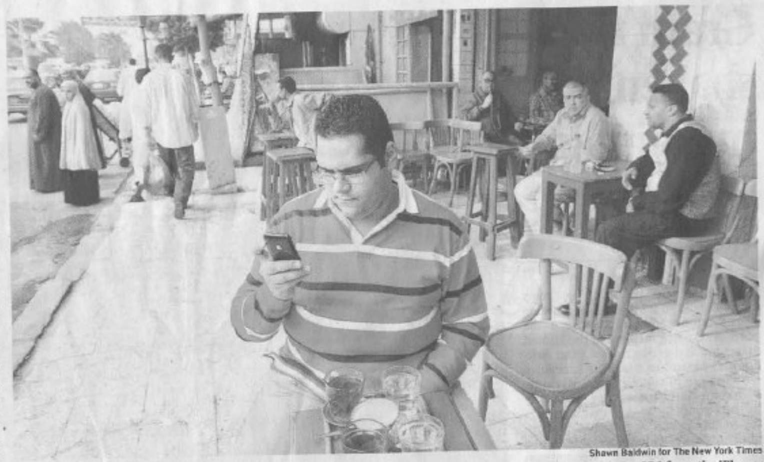
Second, he argued that it was important for technology companies to set principles and follow them. "Here is the big question for Apple: Is this an ad hoc approach, or is there a fundamental policy, balancing the freedom of expression and information with the demands of the government?"

It is easy to get swept up in the utopianism embedded in new technologies. That we will be more politically engaged because of the organizing and fund-raising tools of social networking; that we will think greater thoughts now that anyone can have access to nearly everything ever written; that our tribal hatreds will melt away as the world recognizes that we are all connected.

Even those like Ganesan, who see technology abused, are cautiously hopeful. "Technologies do not hold people accountable. They give people the tools to hold people accountable." But he added: "We believe as a human rights group that the Internet can have an opening and transforming effect."

When Human Rights Watch was founded in 1978, he said, people were "smuggling letters by hand from the Soviet Union — that was how the world found out about a dissident." Today, there is a range of tools for spreading the word, from blogs to e-mail to YouTube videos.

"We may not know what the maximum impact of openness is," he said. "But we do know that in the most closed places the worst things happen."



Shawn Baldwin for The New York Times

Ahmed Gabr, a technology blogger, with his iPhone in Tanta, Egypt. The country asked Apple to remove the GPS from the iPhone.

“Overconfidence in GPS performance (see Wikipedia)

First by demonstrating its exceptional performance, then by becoming popular, GPS has changed the perception of positioning and navigation within society itself. As a result, institutions and public authorities find it increasingly difficult to accept that it is possible to "not know where you are" and in both professional and leisure applications, given its ease of use, GPS has completely relieved practitioners of positioning and navigation tasks from having to perform any tasks at all, this is perhaps the main fault of GPS.

GPS receivers that display position on a basemap also display the direction of travel as a small arrow. In the case of a mobile object that moves slowly, this information is imprecise. In particular, for a human who moves either by walking or running the direction must be considered with great caution. GPS receivers designed for consumer use by hikers that display the position on a base map often have a built-in magnetic compass. Although the display is digital on the screen, it is indeed a magnetic azimuth. It is this information that must be used to orient oneself in the field.

Its use is at the risk and peril of the user and it offers, a priori, no guarantee, nor any liability in the event of an incident. Indeed, despite its reliability and accuracy, such a system cannot be 100% reliable. In addition, its precision can be compromised because the position calculations remain fragile and can be interrupted or disturbed by:

- an external cause of poor reception: interference, storm, high humidity, surrounding relief, magnetic storm (due to solar activity)...;
- intentional or unintentional radio interference;
- a manoeuvrer during which the reception is temporarily masked or scrambled;
- the temporary alignment of some satellites which prevents precise calculation (temporary geometric uncertainty);
- an incident in a satellite.

The French Civil Aviation Accident Investigation and Analysis Bureau has carried out a study on accidents and incidents for which the use of GPS has been identified as a cause or contributing factor. It turns out that in many cases, it was too misplaced confidence in this tool that contributed to the accident or incident. Thus, it is strongly suggested that GPS users and in particular the professionals using it, be clearly informed of the limits of this tool which should only be an aid and not a primary means of navigation.

GPS use has also been implicated in land traffic accidents, including that of a Polish bus on July 22, 2007, causing 26 deaths. The young driver followed the indications of his navigation device, ignoring eleven road signs prohibiting the circulation of coaches.”