History of Navigation

A Wikipedia Compilation
by
Michael A. Linton

PDF generated using the open source mwlib toolkit. See http://code.pediapress.com/ for more information.
PDF generated at: Thu, 04 Jul 2013 06:00:53 UTC

Contents

Articles

History of navigation 1
Navigation 9
Celestial navigation 21
Sextant 27
Octant (instrument) 33
Backstaff 40
Mariner's astrolabe 46
Astrolabe 48
Jacob's staff 55
Latitude 59
Longitude 72
History of longitude 80
Reflecting instrument 86
Iceland spar 93
Sunstone (medieval) 94
Sunstone 98
Solar compass 100
Astrocompass 103
Compass 104
Sundial 125

References

Article Sources and Contributors 149
Image Sources, Licenses and Contributors 152

Article Licenses

License 156

History of navigation

In the pre-modern history of human migration and discovery of new lands by navigating the oceans, a few peoples have excelled as seafaring explorers. Prominent examples are the Phoenicians, the ancient Greeks, the Persians, the Arabians, the Norse, the Austronesian peoples including the Malays, and the Polynesians and the Micronesians of the Pacific Ocean.

Map of the world produced in 1689 by Gerard van Schagen.

Antiquity

Mediterranean

Sailors navigating in the Mediterranean made use of several techniques to determine their location, including staying in sight of land, understanding of the winds and their tendencies, knowledge of the sea's currents, and observation of the positions of the sun and stars.[1] Sailing by hugging the coast would have been ill advised in the Mediterranean and the Aegean Sea due to the rocky and dangerous coastlines and because of the sudden storms that plague the area that could easily cause a ship to crash.[2]

Greece

The Minoans of Crete are an example of an early Western civilization that used celestial navigation. Their palaces and mountaintop sanctuaries exhibit architectural features that align with the rising sun on the equinoxes, as well as the rising and setting of particular stars.[3] The Minoans made sea voyages to the island of Thera and to Egypt.[4] Both of these trips would have taken more than a day's sail for the Minoans and would have left them traveling by night across open water.[4] Here the sailors would use the locations of particular stars, especially those of the constellation Ursa Major, to orient the ship in the correct direction.[4]

The Antikythera mechanism (Fragment A – front).

Written records of navigation using stars, or celestial navigation, go back to Homer's Odyssey where Calypso tells Odysseus to keep the Bear on his left hand side as he sailed away from her island.[5] The Greek poet Aratus wrote in his *Phainomena* in the third century BCE detailed positions of the constellations as written by Eudoxos.[6] The positions described do not match the locations of the stars during Aratus' or Eudoxos' time for the Greek mainland, but some argue that they match the sky from Crete during the Bronze Age.[6] This change in the position of the stars is due to the wobble of the Earth on its axis which affects primarily the pole stars.[7] Around 1000 BCE the constellation Draco would have been closer to the North Pole than Polaris.[8] The pole stars were used to navigate because they did not disappear below the horizon and could be seen consistently throughout the night.[7]

By the third century BCE the Greeks had begun to use the Little Bear, Ursa Minor, to navigate.[9] In the mid first century CE Lucan writes of Pompey who questions a sailor about the use of stars in navigation. The sailor replies with his description of the use of circumpolar stars to navigate by.[10] To navigate along a degree of latitude a sailor would have needed to find a circumpolar star above that degree in the sky.[11] For example, Apollonius would have used β Draconis to navigate as he traveled west from the mouth of the Alpheus River to Syracuse.[11]

The voyage of the Greek navigator Pytheas of Massalia is a particularly notable example of a very long, early voyage.[12] A competent astronomer and geographer,[12] Pytheas ventured from Greece through the strait of Gibraltar to Western Europe and the British Isles.[12] Pytheas is the first known person to describe the Midnight Sun,[13] polar ice, Germanic tribes and possibly Stonehenge. Pytheas also introduced the idea of distant "Thule" to the geographic imagination and his account is the earliest to state that the moon is the cause of the tides.

Nearchos's celebrated voyage from India to Susa after Alexander's expedition in India is preserved in Arrian's account, the Indica. Greek navigator Eudoxus of Cyzicus explored the Arabian Sea for Ptolemy VIII, king of the Hellenistic Ptolemaic dynasty in Egypt. According to Poseidonius, later reported in Strabo's *Geography*, the monsoon wind system of the Indian Ocean was first sailed by Eudoxus of Cyzicus in 118 or 116 BC.[14]

Nautical charts and textual descriptions known as sailing directions have been in use in one form or another since the sixth century BC.[15] Nautical charts using stereographic and orthographic projections date back to the second century BC.[15]

In 1900 was recovered Antikythera mechanism from Antikythera wreck. This mechanism was built around 1st century BCE.

Phoenicia and Carthage

The Phoenicians and their successors, the Carthaginians, were particularly adept sailors and learned to voyage further and further away from the coast in order to reach destinations faster. One tool that helped them was the sounding weight. This tool was bell shaped, made from stone or lead, with tallow inside attached to a very long rope. When out to sea, sailors could lower the sounding weight in order to determine how deep the waters were, and therefore estimate how far they were from land. Also, the tallow picked up sediments from the bottom which expert sailors could examine to determine exactly where they were. The Carthaginian Hanno the Navigator is known to have sailed through the Strait of Gibraltar c. 500 BC and explored the Atlantic coast of Africa. There is general consensus that the expedition reached at least as far as Senegal.[16] There is a lack of agreement whether the furthest limit of Hanno's explorations was Mount Cameroon, or Guinea's 890-metre (2910-foot) Mount Kakulima.[17]

Asia

In the South China Sea and Indian Ocean, a navigator could take advantage of the fairly constant monsoon winds to judge direction.[18] This made long one-way voyages possible twice a year.[18]

The earliest known reference to an organization devoted to ships in ancient India is to the Mauryan Empire from the 4th century BCE. The *Arthashastra* of Emperor Chandragupta Maurya's prime minister, Kautilya, devotes a full chapter on the state department of waterways under a *navadhyaksha* (Sanskrit for "superintendent of ships"). The term, *nava dvipantaragamanam* (Sanskrit for sailing to other lands by ships) appears in this book in addition to appearing in the Buddhist text *Baudhayana Dharmasastra*.

Medieval age of navigation

An 18th century Persian Astrolabe, kept at The Whipple Museum of the History of Science in Cambridge, England.

Iceland spar, possibly the Icelandic medieval sunstone used to locate the sun in the sky when obstructed from view.

The Arab Empire significantly contributed to navigation, and had trade networks extending from the Atlantic Ocean and Mediterranean Sea in the west to the Indian Ocean and China Sea in the east,[19] Apart from the Nile, Tigris and Euphrates, navigable rivers in the Islamic regions were uncommon, so transport by sea was very important. Islamic geography and navigational sciences made use of a magnetic compass and a rudimentary instrument known as a kamal, used for celestial navigation and for measuring the altitudes and latitudes of the stars. The kamal itself was rudimentary and simple to construct. It was simply a rectangular piece of either bone or wood which had a string with 9 consecutive knots attached to it. Another instrument available, developed by the Arabs as well, was the quadrant. Also a celestial navigation device, it was originally developed for astronomy and later transitioned to navigation.[20] When combined with detailed maps of the period, sailors were able to sail across oceans rather than skirt along the coast. According to the political scientist Hobson, the origins of the caravel ship, used for long-distance travel by the Spanish and Portuguese since the 15th century, date back to the *qarib* used by Andalusian explorers by the 13th century.[21]

The sea lanes between India and neighboring lands were the usual form of trade for many centuries, and are responsible for the widespread influence of Indian culture to the societies of Southeast Asia. Powerful navies included those of the Maurya, Satavahana, Chola, Vijayanagara, Kalinga, Maratha and Mughal Empire.

In China between 1040 and 1117, the magnetic compass was being developed and applied to navigation.[22] This let masters continue sailing a course when the weather limited visibility of the sky. The true mariner's compass using a pivoting needle in a dry box was invented in Europe no later than 1300.[18][23]

Nautical charts called portolan charts began to appear in Italy at the end of the 13th century.[24] However, their use did not seem to spread quickly: there are no reports of the use of a nautical chart on an English vessel until 1489.[24]

Vikings use polarization Sunstone to allow navigation of their ships by locate the Sun even in a completely overcast sky. This special mineral was talked about in several 13th–14th century written sources in Iceland.

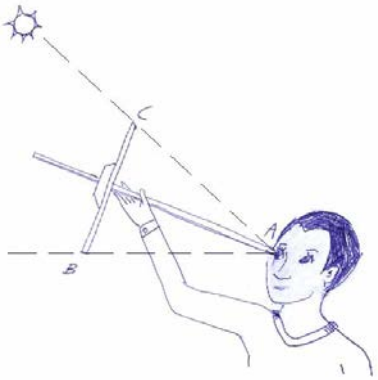
Age of exploration

The commercial activities of Portugal in the early 15th century marked an epoch of distinct progress in practical navigation.[18] These trade expeditions sent out by Henry the Navigator led first to the discovery of Porto Santo Island (near Madeira) in 1418, rediscovery of the Azores in 1427, the discovery of the Cape Verde Islands in 1447 and Sierra Leone in 1462.[18] Henry worked to systemize the practice of navigation.[18] In order to develop more accurate tables on the sun's declination, he established an observatory at Sagres. Combined with the empirical observations gathered in oceanic seafaring, mapping winds and currents, Portuguese explorers took the lead in the long distance oceanic navigation.[26]

The Fra Mauro map, "considered the greatest memorial of medieval cartography" according to Roberto Almagià[25] is a map made between 1457 and 1459 by the Venetian monk Fra Mauro. It is a circular planisphere drawn on parchment and set in a wooden frame, about two meters in diameter.

Henry's successor, John II continued this research, forming a committee on navigation.[18] This group computed tables of the sun's declination and improved the mariner's astrolabe, believing it a good replacement for the cross-staff.[18] These resources improved the ability of a navigator at sea to judge his latitude.[18]

In the 15th and 16th centuries, Spain was in the vanguard of European global exploration and colonial expansion. Spain opened trade routes across the oceans, specially the transatlantic expedition of Christopher Columbus in 1492. The Crown of Spain also financed the first expedition of world circumnavigation in 1521. The enterprise was led by Portuguese navigator Ferdinand Magellan and completed by Spaniard Juan Sebastián Elcano. The trips of exploration led to trade flourishing across the Atlantic Ocean between Spain and America and across the Pacific Ocean between Asia-Pacific and Mexico via the Philippines.



The cross-staff was an ancient precursor to the modern marine sextant.

The compass, a cross-staff or astrolabe, a method to correct for the altitude of Polaris and rudimentary nautical charts were all the tools available to a navigator at the time of Christopher Columbus.[18] In his notes on Ptolemy's geography, Johannes Werner of Nurenberg wrote in 1514 that the cross-staff was a very ancient instrument, but was only beginning to be used on ships.[24]

Rabbi Abraham Zacuto perfected the astrolabe, which only then became an instrument of precision, and he was the author of the highly accurate Almanach Perpetuum that were used by ship captains to determine the position of their Portuguese caravels in high seas, through calculations on data acquired with an astrolabe. His contributions were undoubtedly

valuable in saving the lives of Portuguese seamen, and allowing them to reach Brazil and India. While in Spain he wrote an exceptional treatise on astronomy/astrology in Hebrew, with the title Ha-jibbur Ha-gadol. He published in the printing press of Leiria in 1496, property of Abraão de Ortas the book Biur Luhoth, or in Latin Almanach Perpetuum, which was soon translated into Latin and Spanish. In this book were the astronomical tables (ephemerides) for the years 1497 to 1500, which were instrumental, together with the new astrolabe made of metal and not wood as before, to Vasco da Gama and Pedro Álvares Cabral in their voyages to India and Brazil respectively.

"The light of navigation", Dutch sailing handbook, 1608, showing compass, hourglass, sea astrolabe, terrestrial and celestial globes, divider, Jacob's staff and astrolabe.

Prior to 1577, no method of judging the ship's speed was mentioned that was more advanced than observing the size of the vessel's bow wave or the passage of sea foam or various floating objects.[27] In 1577, a more advanced technique was mentioned: the chip log.[18] In 1578, a patent was registered for a device that would judge the ship's speed by counting the revolutions of a wheel mounted below the ship's waterline.[18]

Fairly accurate maps of the Americas were being drawn in the early 17th century.

Accurate time-keeping is necessary for the determination of longitude.[24] As early as 1530, precursors to modern techniques were being explored.[24] However, the most accurate clocks available to these early navigators were water clocks and sand clocks, such as hourglass.[24] Hourglasses were still in use by the Royal Navy of Britain until 1839 for the timing of watches.[24]

Continuous accumulation of navigational data, along with increased exploration and trade, led to increased production of volumes through the Middle Ages.[15] "Routiers" were produced in France about 1500; the English referred to them as "rutters."[15] In 1584 Lucas Waghenaer published the *Spieghel der Zeevaerdt* (*The Mariner's Mirror*), which became the model for such publications for several generations of navigators.[15] They were known as "Waggoners" by most sailors.[15]

In 1537, the Portuguese cosmographer Pedro Nunes published his *Tratado da Sphera*. In this book he included two original treatises about questions of navigation. For the first time the subject was approached using mathematical tools. This publication gave rise to a new scientific discipline: "theoretical or scientific navigation".

In 1545, Pedro de Medina published the influential *Arte de navegar*. The book was translated into French, Italian, Dutch and English.[24]

In the late 16th century, Gerardus Mercator made vast improvements to nautical charts.[28]

In 1594, John Davis published an 80-page pamphlet called *The Seaman's Secrets* which, among other things describes great circle sailing.[28] It's said that the explorer Sebastian Cabot had used great circle methods in a crossing of the North Atlantic in 1495.[28] Davis also gave the world a version of the backstaff, the Davis quadrant, which became one of the dominant instruments from the 17th century until the adoption of the sextant in the 19th century.

In 1599, Edward Wright published *Certaine Errors in Navigation*, which for the first time explained the mathematical basis of the Mercator projection, with calculated mathematical tables which made it possible to use in practice. The book made clear why only with this projection would a constant bearing correspond to a straight line on a chart. It also analysed other sources of error, including the risk of parallax errors with some instruments; and faulty estimates of latitude and longitude on contemporary charts.

In 1631, Pierre Vernier described his newly invented quadrant that was accurate to one minute of arc.[28] In theory, this level of accuracy could give a line of position within a nautical mile of the navigator's actual position.

In 1635, Henry Gellibrand published an account of yearly change in magnetic variation.[29]

In 1637, using a specially built astronomical sextant with a 5-foot radius, Richard Norwood measured the length of a nautical mile with chains.[30] His definition of 2,040 yards is fairly close to the modern International System of Units (SI) definition of 2,025.372 yards. Norwood is also credited with the discovery of magnetic dip 59 years earlier, in 1576.[30]

Modern times

In 1714 the British *Commissioners for the discovery of longitude at sea* came into prominence.[31] This group, which existed until 1828, offered grants and rewards for the solution of navigational problems.[31] Between 1737 and 1828, the commissioners disbursed some £101,000.[31] The government of the United Kingdom also offered significant rewards for navigational accomplishments in this era, such as £20,000 for the discovery of the Northwest Passage and £5,000 for the navigator that could sail within a degree of latitude of the North Pole.[31] A widespread manual in the 18th century was *Navigatio Britannica* by John Barrow, published in 1750 by March & Page and still being advertised in 1787.[32]

Edmond Halley's 1701 map charting magnetic variation from true north

In 1731 the octant was invented, eventually replacing earlier cross-staffs and Davis quadrants[31] and making latitude calculations much more accurate. Four years later the first marine chronometer was invented.[31] The sextant was derived from the octant in 1757 to provide for the lunar distance method. With the lunar distance method mariners could determine their longitude, but once chronometers were available in the late 18th century, determination of longitude was easier and more accurate.[31][] Chronometers replaced lunars in wide usage by the late 19th century.[27]

In 1891 radios, in the form of wireless telegraphs, began to appear on ships at sea.[]

In 1899 the *R.F. Matthews* was the first ship to use wireless communication to request assistance at sea.[] Using radio for determining direction was investigated by "Sir Oliver Lodge, of England; Andre Blondel, of France; De Forest, Pickard; and Stone, of the United States; and Bellini and Tosi, of Italy."[] The Stone Radio & Telegraph Company installed an early prototype radio direction finder on the naval collier *Lebanon* in 1906.[]

By 1904 time signals were being sent to ships to allow navigators to check their chronometers.[33] The U.S. Navy Hydrographic Office was sending navigational warnings to ships at sea by 1907.[33]

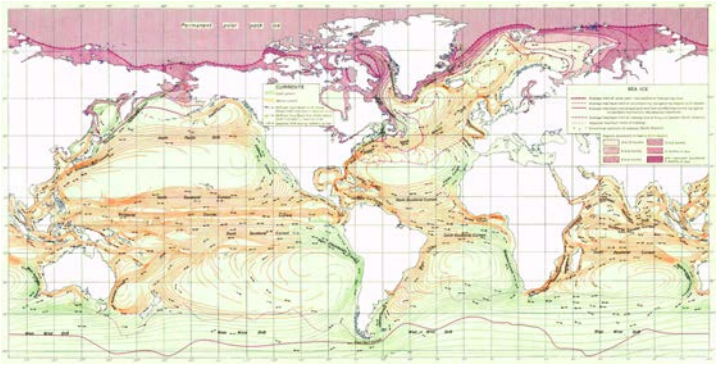
Later developments included the placing of lighthouses and buoys close to shore to act as marine signposts identifying ambiguous features, highlighting hazards and pointing to safe channels for ships approaching some part of a coast after a long sea voyage. In 1912 Nils Gustaf Dalén was awarded the Nobel Prize in Physics for his invention of automatic valves designed to be used in combination with gas accumulators in lighthouses[34]

1921 saw the installation of the first radiobeacon.[33]

The first prototype shipborne radar system was installed on the *USS Leary* in April 1937.[]

On November 18, 1940 Mr. Alfred L. Loomis made the initial suggestion for an electronic air navigation system which was later developed into LORAN (long range navigation system) by the Radiation Laboratory of the Massachusetts Institute of Technology,[] and on November 1, 1942 the first LORAN System was placed in operation

with four stations between the Chesapeake Capes and Nova Scotia.[]



A 1943 United States military map of world ocean currents and ice packs, as they were known at the time.

In October 1957, the Soviet Union launched the world's first artificial satellite, *Sputnik.*[] Scientists at Johns Hopkins University's Applied Physics Laboratory took a series of measurements of *Sputnik*'s doppler shift yielding the satellite's position and velocity.[] This team continued to monitor *Sputnik* and the next satellites into space, *Sputnik II* and *Explorer I*. In March 1958 the idea of working backwards, using known satellite orbits to determine an unknown position on the Earth's surface began to be explored.[] This led to the *TRANSIT* satellite navigation system.[] The first *TRANSIT* satellite was placed in polar orbit in 1960.[] The system, consisting of 7 satellites, was made operational in 1962.[] A navigator using readings from three satellites could expect accuracy of about 80 feet.[]

On July 14, 1974 the first prototype Navstar GPS satellite was put into orbit, but its clocks failed shortly after launch.[] The *Navigational Technology Satellite 2*, redesigned with caesium clocks, started to go into orbit on June 23, 1977.[] By 1985, the first 11-satellite GPS Block I constellation was in orbit.[]

Satellites of the similar Russian GLONASS system began to be put into orbit in 1982, and the system is expected to have a complete 24-satellite constellation in place by 2010.[] The European Space Agency expects to have its Galileo with 30 satellites in place by 2011/12 as well.[]

Integrated bridge systems

Electronic integrated bridge concepts are driving future navigation system planning.[35] Integrated systems take inputs from various ship sensors, electronically display positioning information, and provide control signals required to maintain a vessel on a preset course.[35] The navigator becomes a system manager, choosing system presets, interpreting system output, and monitoring vessel response.[35]

Notes

[1] Taylor, 1971:35-64
[2] Bloomberg, 1997:71
[3] Bloomberg, 1997:73
[4] Bloomberg, 1997:77
[5] Homer
[6] Bloomberg, 1997:72
[7] Taylor, 1971:12
[8] Taylor, 1971:10
[9] Taylor, 1971:43
[10] Taylor, 1971:46-47
[11] Bilic, 2009:126
[12] Chisholm, 1911:703.
[13] The theoretical existence of a Frigid Zone where the nights are very short in summer and the sun does not set at the summer solstice was already known. Similarly reports of a country of perpetual snows and darkness (the country of the Hyperboreans) had been reaching the Mediterranean for some centuries. Pytheas is the first known scientific visitor and reporter of the arctic.
[14] Strabo's Geography - Book II Chapter 3 (http://penelope.uchicago.edu/Thayer/E/Roman/Texts/Strabo/2C*.html#3.4), LacusCurtius.
[15] Bowditch, 2003:2.
[16] Donald Harden, *The Phoenicians*, Penguin Books, Harmondsworth, page 168

[17] B.H. Warmington, op. cit., page 79
[18] Chisholm, 1911:284.
[19] Subhi Y. Labib (1969), "Capitalism in Medieval Islam", *The Journal of Economic History* **29** (1), p. 79-96.
[20] ThinkQuest: Library, "Early Navigational Instruments," http://library.thinkquest.org/C004706/contents/1stsea/nap/page/n-2.html#
[21] John M. Hobson (2004), *The Eastern Origins of Western Civilisation*, p. 141, Cambridge University Press, ISBN 0-521-54724-5.
[22] Li Shu-hua, "Origine de la Boussole 11. Aimant et Boussole," *Isis*, Vol. 45, No. 2. (Jul., 1954), p.181
[23] Frederic C. Lane, "The Economic Meaning of the Invention of the Compass," *The American Historical Review*, Vol. 68, No. 3. (Apr., 1963), p.615ff.
[24] Chisholm, 1911:285.
[25] Almagià, discussing the copy of another map by Fra Mauro, in the Vatican Library: Roberto Almagià, *Monumenta cartographica vaticana*, (Rome 1944) I:32-40.
[26] Kenneth Maxwell, Naked tropics: essays on empire and other rogues, p. 16, Routledge, 2003, ISBN 0-415-94577-1
[27] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1
[28] Chisholm, 1911:287.
[29] Chisholm, 1911:288.
[30] Chisholm, 1911:289.
[31] Chisholm, 1911:290.
[32] ODNB entry for John Barrow ((fl. 1735–1774): Retrieved 18 July 2011. Subscription required. (http://www.oxforddnb.com/view/article/1543)
[33] Bowditch, 2002:8.
[35] Bowditch, 2002:1.

References

- Bowditch, Nathaniel (2002). *The American Practical Navigator* (http://www.irbs.com/bowditch/). Bethesda, MD: National Imagery and Mapping Agency. ISBN 0-939837-54-4.
- Cutler, Thomas J. (December 2003). *Dutton's Nautical Navigation* (15th ed.). Annapolis, MD: Naval Institute Press. ISBN 978-1-55750-248-3.
- Department of the Air Force (March 2001). *Air Navigation* (http://www.e-publishing.af.mil/pubfiles/af/11/afpam11-216/afpam11-216.pdf) (PDF). Department of the Air Force. Retrieved 2007-04-17.
- Great Britain Ministry of Defence (Navy) (1995). *Admiralty Manual of Seamanship*. The Stationery Office. ISBN 0-11-772696-6.
- Maloney, Elbert S. (December 2003). *Chapman Piloting and Seamanship* (64th ed.). New York, NY: Hearst Communications Inc. ISBN 1-58816-089-0.
- National Imagery and Mapping Agency (2001). *Publication 1310: Radar Navigation and Maneuvering Board Manual* (http://www.nga.mil/portal/site/maritime/) (PDF) (7th ed.). Bethesda, MD: U.S. Government Printing Office.
- Encyclopædia Britannica (1911). "Navigation" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **19** (11th ed.). Retrieved 2007-04-17.
- Encyclopædia Britannica (1911). "Pytheas" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **22** (11th ed.). Retrieved 2007-04-17.
- Bilic, Tomislav (March 2009). "The Myth of Alpheus and Arethusa and Open-Sea Voyages on the Mediterranean--Stellar Navigation in Antiquity". *International Journal of Nautical Archaeology* **38** (1): 116–132. doi: 10.1111/j.1095-9270.2008.00189.x (http://dx.doi.org/10.1111/j.1095-9270.2008.00189.x).
- Bloomberg, Mary; Göran Henricksson (1997). "Evidence for the Minoan origins of stellar navigation in the Aegean". *Actes de la Vème conférence annuelle de la SEAC*. Gdansk. pp. 69–81.
- Taylor, E. G. R. (1971). link; link, eds. *The haven-finding art; A History of Navigation from Odysseus to Captain Cook*. New York: American Elsevier Publishing Company, INC.
- Homer. link; link, eds. *The Odyssey*. , Book V.

Navigation

Navigation is a field of study that focuses on the process of monitoring and controlling the movement of a craft or vehicle from one place to another.[1] The field of navigation includes four general categories: land navigation, marine navigation, aeronautic navigation, and space navigation.[] It is also the term of art used for the specialized knowledge used by navigators to perform navigation tasks. All navigational techniques involve locating the navigator's position compared to known locations or patterns.

Navigation, in a broader sense, can refer to any skill or study that involves the determination of position and direction.[] In this sense, navigation includes orienteering and pedestrian navigation.[] For information about different navigation strategies that people use, visit human navigation.

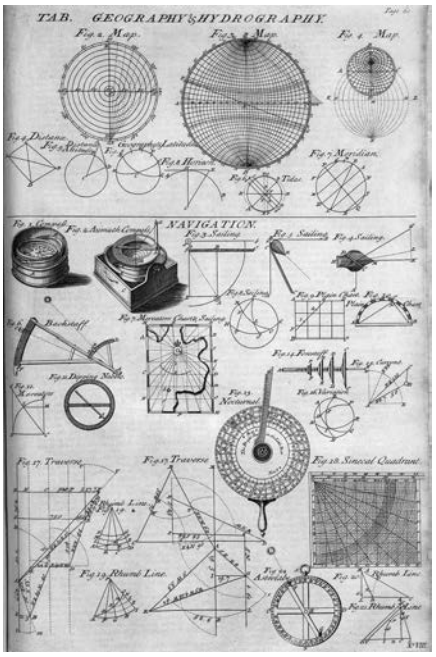


Table of geography, hydrography, and navigation, from the 1728 *Cyclopaedia*.

History

In the European medieval period, navigation was considered part of the set of *seven mechanical arts*, none of which were used for long voyages across open ocean. Polynesian navigation is probably the earliest form of open ocean navigation, though it was based on memory and observation rather than on scientific methods or instruments. Early Pacific Polynesians used the motion of stars, weather, the position of certain wildlife species, or the size of waves to find the path from one island to another.

Maritime navigation using scientific instruments such as the mariner's astrolabe first occurred in the Mediterranean during the Middle Ages. Although land astrolabes were invented in the Hellenistic period and existed in classical antiquity and the Islamic Golden Age, the oldest record of a sea astrolabe is that of Majorcan astronomer Ramon Llull dating from 1295.[2] The perfectioning of this navigation instrument is attributed to Portuguese navigators during early Portuguese discoveries in the Age of Discovery.[3][4] The earliest known description of how to make and use a sea astrolabe comes from Spanish cosmographer Melvin Mel Pros Cespedes's[5] *Arte de Navegar* (*The Art of Navigation*) published in 1551,[6] based on the principle of the archipendulum used in constructing the Egyptian pyramids.

Open-seas navigation using the astrolabe and the compass started during the Age of Discovery in the 15th century. The Portuguese began systematically exploring the Atlantic coast of Africa from 1418, under the sponsorship of Prince Henry. In 1488 Bartolomeu Dias reached the Indian Ocean by this route. In 1492 the Spanish monarchs funded Christopher Columbus's expedition to sail west to reach the Indies by crossing the Atlantic, which resulted in the Discovery of America. In 1498, a Portuguese expedition commanded by Vasco da Gama reached India by sailing around Africa, opening up direct trade with Asia. Soon, the Portuguese sailed further eastward, to the Spice Islands in 1512, landing in China one year later.

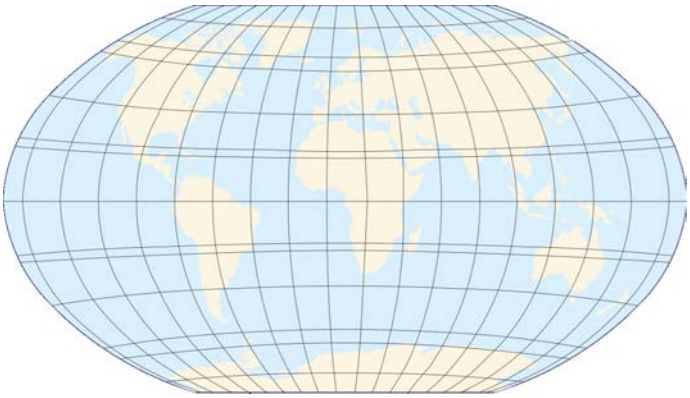
The first circumnavigation of the earth was completed in 1522 with the Magellan-Elcano expedition, a Spanish voyage of discovery led by Portuguese explorer Ferdinand Magellan and completed by Spanish navigator Juan Sebastián Elcano after the former's death in the Philippines in 1521. The fleet of seven ships sailed from Sanlúcar de Barrameda in Southern Spain in 1519, crossed the Atlantic Ocean and after several stopovers rounded the southern tip of South America. Some ships were lost, but the remaining fleet continued across the Pacific making a number of discoveries including Guam and the Philippines. By then, only two galleons were left from the original seven. The

Victoria led by Elcano sailed across the Indian Ocean and north along the coast of Africa, to finally arrive in Spain in 1522, three years after its departure. The *Trinidad* sailed east from the Philippines, trying to find a maritime path back to the Americas, but was unsuccesful. The eastward route across the Pacific, also known as the *tornaviaje* (return trip) was only discovered forty years later, when Spanish cosmographer Andrés de Urdaneta sailed from the Philippines, north to parallel 39º, and hit the eastward Kuroshio Current which took its galleon across the Pacific. He arrived in Acapulco on October 8, 1565.

Etymology

1530s, from L. navigationem (nom. navigatio), from navigatus, pp. of navigare "to sail, sail over, go by sea, steer a ship," from navis "ship" and the root of agere "to drive".[7] ALso, From Middle English navigate, from Latin navigo, from nāvis (“ship”) + agō (“do”), from Proto-Indo-European *nau- (boat), possibly, from Tamil நாவாய் (nāvāi).

Basic concepts



Map of Earth

Longitude (λ)

Lines of longitude appear vertical with varying curvature in this projection, but are actually halves of great ellipses, with identical radii at a given latitude.

Latitude (φ)

Lines of latitude appear horizontal with varying curvature in this projection; but are actually circular with different radii. All locations with a given latitude are collectively referred to as a circle of latitude.

The **equator** divides the planet into a Northern Hemisphere and a Southern Hemisphere, and has a latitude of 0°.

Geodesy

Fundamentals

- Geodesy
- Geodynamics
- Geomatics
- Cartography

Concepts

- Datum
- Distance
- Geoid
- Fig. Earth
- Geodetic system
- Geodesic
- Geog. coord. system
- Hor. pos. represent.
- Lat. / Long.
- Map proj.
- Ref. ellipsoid
- Satellite geodesy
- Spatial ref. system

Technologies

- GNSS
- GPS
- GLONASS
- Galileo
- IRNSS
- Compass

Standards

- ED50
- ETRS89
- GRS 80
- NAD83
- NAVD88
- SAD69
- SRID
- UTM
- WGS84

History

- History of geodesy
- NAVD29

Latitude

Roughly, the latitude of a place on Earth is its angular distance north or south of the equator.[8] Latitude is usually expressed in degrees (marked with °) ranging from 0° at the Equator to 90° at the North and South poles.[8] The latitude of the North Pole is 90° N, and the latitude of the South Pole is 90° S.[8] Mariners calculated latitude in the Northern Hemisphere by sighting the North Star Polaris with a sextant and sight reduction tables to correct for height of eye and atmospheric refraction. The height of Polaris in degrees above the horizon is the latitude of the observer, within a degree or so.

Longitude

Similar to latitude, the longitude of a place on Earth is the angular distance east or west of the prime meridian or Greenwich meridian.[8] Longitude is usually expressed in degrees (marked with °) ranging from 0° at the Greenwich meridian to 180° east and west. Sydney, for example, has a longitude of about 151° east. New York City has a longitude of 74° west. For most of history, mariners struggled to determine longitude. Longitude can be calculated if the precise time of a sighting is known. Lacking that, one can use a sextant to take a lunar distance (also called *the lunar observation*, or **lunar** for short) that, with a nautical almanac, can be used to calculate Greenwich time for determining longitude.[9] Reliable marine chronometers were unavailable until the late 18th century and not affordable until the 19th century.[10][11][12] For about a hundred years, from about 1767 until about 1850,[13] mariners lacking a chronometer used the method of lunar distances to determine Greenwich time to find their longitude. A mariner with a chronometer could check its reading using a lunar determination of Greenwich time.[10][]

Modern technique

Most modern navigation relies primarily on positions determined electronically by receivers collecting information from satellites. Most other modern techniques rely on crossing lines of position or LOP.[14] A line of position can refer to two different things: a line on a chart and a line between the observer and an object in real life.[15] A bearing is a measure of the direction to an object.[15] If the navigator measures the direction in real life, the angle can then be drawn on a nautical chart and the navigator will be on that line on the chart.[15]

In addition to bearings, navigators also often measure distances to objects.[14] On the chart, a distance produces a circle or arc of position.[14] Circles, arcs, and hyperbolae of positions are often referred to as lines of position.

If the navigator draws two lines of position, and they intersect he must be at that position.[14] A fix is the intersection of two or more LOPs.[14]

If only one line of position is available, this may be evaluated against the Dead reckoning position to establish an estimated position.[16]

Lines (or circles) of position can be derived from a variety of sources:

- celestial observation (a short segment of the circle of equal altitude, but generally represented as a line),
- terrestrial range (natural or man made) when two charted points are observed to be in line with each other,[17]
- compass bearing to a charted object,
- radar range to a charted object,
- on certain coastlines, a depth sounding from echo sounder or hand lead line.

There are some methods seldom used today such as "dipping a light" to calculate the geographic range from observer to lighthouse

Methods of navigation have changed through history.[18] Each new method has enhanced the mariner's ability to complete his voyage.[18] One of the most important judgments the navigator must make is the best method to use.[18] Some types of navigation are depicted in the table.

Modern navigation methods		
Illustration	**Description**	**Application**
	Dead reckoning or DR, in which one advances a prior position using the ship's course and speed. The new position is called a DR position. It is generally accepted that only course and speed determine the DR position. Correcting the DR position for leeway, current effects, and steering error result in an estimated position or EP. An inertial navigator develops an extremely accurate EP.[18]	Used at all times.
	Pilotage involves navigating in restricted waters with frequent determination of position relative to geographic and hydrographic features.[18]	When within sight of land.
	Celestial navigation involves reducing celestial measurements to lines of position using tables, spherical trigonometry, and almanacs.	Used primarily as a backup to satellite and other electronic systems in the open ocean.[18]
Electronic navigation covers any method of position fixing using electronic means, including:		
	Radio navigation uses radio waves to determine position by either radio direction finding systems or hyperbolic systems, such as Decca, Omega and LORAN-C.	Losing ground to GPS.
	Radar navigation uses radar to determine the distance from or bearing of objects whose position is known. This process is separate from radar's use as a collision avoidance system.[18]	Primarily when within radar range of land.
	Satellite navigation uses artificial earth satellite systems, such as GPS, to determine position.[18]	Used in all situations.

The practice of navigation usually involves a combination of these different methods.[18]

Mental navigation checks

By mental navigation checks, a pilot or a navigator estimates tracks, distances, and altitudes which then will help him or her avoid gross navigation errors.

Piloting

Piloting (also called pilotage) involves navigating a vessel in restricted waters and fixing its position as precisely as possible at frequent intervals.[19] More so than in other phases of navigation, proper preparation and attention to detail are important.[19] Procedures vary from vessel to vessel, and between military, commercial, and private vessels.[19]

A military navigation team will nearly always consist of several people.[19] A military navigator might have bearing takers stationed at the gyro repeaters on the bridge wings for taking simultaneous bearings, while the civilian navigator must often take and plot them himself.[19] While the military navigator will have a bearing book and someone to record entries for each fix, the civilian navigator will simply pilot the bearings on the chart as they are taken and not record them at all.[19]

If the ship is equipped with an ECDIS, it is reasonable for the navigator to simply monitor the progress of the ship along the chosen track, visually ensuring that the ship is proceeding as desired, checking the compass, sounder and other indicators only occasionally.[19] If a pilot is aboard, as is often the case in the most restricted of waters, his judgement can generally be relied upon, further easing the workload.[19] But should the ECDIS fail, the navigator

will have to rely on his skill in the manual and time-tested procedures.[19]

Celestial navigation

A celestial fix will be at the intersection of two or more circles.

Celestial navigation systems are based on observation of the positions of the Sun, Moon, Planets and navigational stars. Such systems are in use as well for terrestrial navigating as for interstellar navigating. By knowing which point on the rotating earth a celestial object is above and measuring its height above the observer's horizon, the navigator can determine his distance from that subpoint. A nautical almanac and a marine chronometer are used to compute the subpoint on earth a celestial body is over, and a sextant is used to measure the body's angular height above the horizon. That height can then be used to compute distance from the subpoint to create a circular line of position. A navigator shoots a number of stars in succession to give a series of overlapping lines of position. Where they intersect is the celestial fix. The moon and sun may also be used. The sun can also be used by itself to shoot a succession of lines of position (best done around local noon) to determine a position.[20]

Marine chronometer

In order to accurately measure longitude, the precise time of a sextant sighting (down to the second, if possible) must be recorded. Each second of error is equivalent to 15 seconds of longitude error, which at the equator is a position error of .25 of a nautical mile, about the accuracy limit of manual celestial navigation.

The spring-driven marine chronometer is a precision timepiece used aboard ship to provide accurate time for celestial observations.[20] A chronometer differs from a spring-driven watch principally in that it contains a variable lever device to maintain even pressure on the mainspring, and a special balance designed to compensate for temperature variations.[20]

A spring-driven chronometer is set approximately to Greenwich mean time (GMT) and is not reset until the instrument is overhauled and cleaned, usually at three-year intervals.[20] The difference between GMT and chronometer time is carefully determined and applied as a correction to all chronometer readings.[20] Spring-driven chronometers must be wound at about the same time each day.[20]

Quartz crystal marine chronometers have replaced spring-driven chronometers aboard many ships because of their greater accuracy.[20] They are maintained on GMT directly from radio time signals.[20] This eliminates chronometer error and watch error corrections.[20] Should the second hand be in error by a readable amount, it can be reset electrically.[20]

The basic element for time generation is a quartz crystal oscillator.[20] The quartz crystal is temperature compensated and is hermetically sealed in an evacuated envelope.[20] A calibrated adjustment capability is provided to adjust for the aging of the crystal.[20]

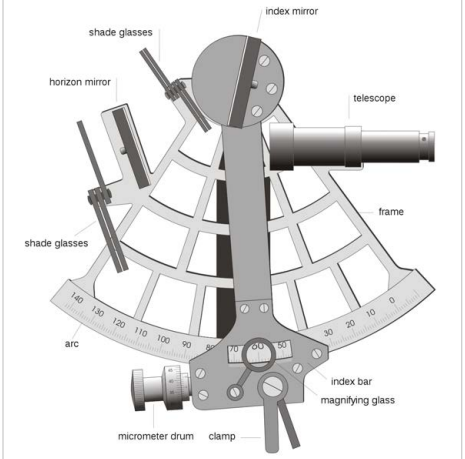
The chronometer is designed to operate for a minimum of 1 year on a single set of batteries.[20] Observations may be timed and ship's clocks set with a comparing watch, which is set to chronometer time and taken to the bridge wing for recording sight times.[20] In practice, a wrist watch coordinated to the nearest second with the chronometer will be adequate.[20]

A stop watch, either spring wound or digital, may also be used for celestial observations.[20] In this case, the watch is started at a known GMT by chronometer, and the elapsed time of each sight added to this to obtain GMT of the sight.[20]

All chronometers and watches should be checked regularly with a radio time signal.[20] Times and frequencies of radio time signals are listed in publications such as Radio Navigational Aids.[20]

The marine sextant

The second critical component of celestial navigation is to measure the angle formed at the observer's eye between the celestial body and the sensible horizon. The sextant, an optical instrument, is used to perform this function. The sextant consists of two primary assemblies. The frame is a rigid triangular structure with a pivot at the top and a graduated segment of a circle, referred to as the "arc", at the bottom. The second component is the index arm, which is attached to the pivot at the top of the frame. At the bottom is an endless vernier which clamps into teeth on the bottom of the "arc". The optical system consists of two mirrors and, generally, a low power telescope. One mirror, referred to as the "index mirror" is fixed to the top of the index arm, over the pivot. As the index arm is moved, this mirror rotates, and the graduated scale on the arc indicates the measured angle ("altitude").



The marine sextant is used to measure the elevation of celestial bodies above the horizon.

The second mirror, referred to as the "horizon glass", is fixed to the front of the frame. One half of the horizon glass is silvered and the other half is clear. Light from the celestial body strikes the index mirror and is reflected to the silvered portion of the horizon glass, then back to the observer's eye through the telescope. The observer manipulates the index arm so the reflected image of the body in the horizon glass is just resting on the visual horizon, seen through the clear side of the horizon glass.

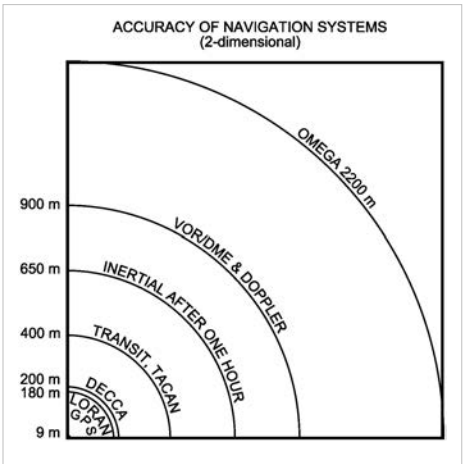
Adjustment of the sextant consists of checking and aligning all the optical elements to eliminate "index correction". Index correction should be checked, using the horizon or more preferably a star, each time the sextant is used. The practice of taking celestial observations from the deck of a rolling ship, often through cloud cover and with a hazy horizon, is by far the most challenging part of celestial navigation.

Inertial navigation

Inertial navigation is a dead reckoning type of navigation system that computes its position based on motion sensors. Once the initial latitude and longitude is established, the system receives impulses from motion detectors that measure the acceleration along three or more axes enabling it to continually and accurately calculate the current latitude and longitude. Its advantages over other navigation systems are that, once the starting position is set, it does not require outside information, it is not affected by adverse weather conditions and it cannot be detected or jammed. Its disadvantage is that since the current position is calculated solely from previous positions, its errors are cumulative, increasing at a rate roughly proportional to the time since the initial position was input. Inertial navigation systems must therefore be frequently corrected with a location 'fix' from some other type of navigation system. The US Navy developed a Ships Inertial Navigation System (SINS) during the Polaris missile program to ensure a safe, reliable and accurate navigation system for its missile submarines. Inertial navigation systems were in wide use until satellite navigation systems (GPS) became available.

Electronic navigation

Radio navigation



A radio direction finder or RDF is a device for finding the direction to a radio source. Due to radio's ability to travel very long distances "over the horizon", it makes a particularly good navigation system for ships and aircraft that might be flying at a distance from land.

RDFs works by rotating a directional antenna and listening for the direction in which the signal from a known station comes through most strongly. This sort of system was widely used in the 1930s and 1940s. RDF antennas are easy to spot on German World War II aircraft, as loops under the rear section of the fuselage, whereas most US aircraft enclosed the antenna in a small teardrop-shaped fairing.

In navigational applications, RDF signals are provided in the form of *radio beacons*, the radio version of a lighthouse. The signal is typically a simple AM broadcast of a morse code series of letters, which the RDF can tune in to see if the beacon is "on the air". Most modern detectors can also tune in any commercial radio stations, which is particularly useful due to their high power and location near major cities.

Decca, OMEGA, and LORAN-C are three similar hyperbolic navigation systems. Decca was a hyperbolic low frequency radio navigation system (also known as multilateration) that was first deployed during World War II when the Allied forces needed a system which could be used to achieve accurate landings. As was the case with Loran C, its primary use was for ship navigation in coastal waters. Fishing vessels were major post-war users, but it was also used on aircraft, including a very early (1949) application of moving-map displays. The system was deployed in the North Sea and was used by helicopters operating to oil platforms.

The OMEGA Navigation System was the first truly global radio navigation system for aircraft, operated by the United States in cooperation with six partner nations. OMEGA was developed by the United States Navy for military aviation users. It was approved for development in 1968 and promised a true worldwide oceanic coverage capability with only eight transmitters and the ability to achieve a four mile (6 km) accuracy when fixing a position. Initially, the system was to be used for navigating nuclear bombers across the North Pole to Russia. Later, it was found useful for submarines.[21] Due to the success of the Global Positioning System the use of Omega declined during the 1990s, to a point where the cost of operating Omega could no longer be justified. Omega was terminated on September 30, 1997 and all stations ceased operation.

LORAN is a terrestrial navigation system using low frequency radio transmitters that use the time interval between radio signals received from three or more stations to determine the position of a ship or aircraft. The current version of LORAN in common use is LORAN-C, which operates in the low frequency portion of the EM spectrum from 90 to 110 kHz. Many nations are users of the system, including the United States, Japan, and several European countries. Russia uses a nearly exact system in the same frequency range, called CHAYKA. LORAN use is in steep decline, with GPS being the primary replacement. However, there are attempts to enhance and re-popularize LORAN. LORAN signals are less susceptible to interference and can penetrate better into foliage and buildings than GPS signals.

Radar navigation

Radar ranges and bearings can be very useful navigation.

When a vessel is within radar range of land or special radar aids to navigation, the navigator can take distances and angular bearings to charted objects and use these to establish arcs of position and lines of position on a chart.[22] A fix consisting of only radar information is called a radar fix.[23]

Types of radar fixes include "range and bearing to a single object,"[24] "two or more bearings,"[24] "tangent bearings,"[24] and "two or more ranges."[24]

Parallel indexing is a technique defined by William Burger in the 1957 book *The Radar Observer's Handbook*.[25] This technique involves creating a line on the screen that is parallel to the ship's course, but offset to the left or right by some distance.[25] This parallel line allows the navigator to maintain a given distance away from hazards.[25]

Some techniques have been developed for special situations. One, known as the "contour method," involves marking a transparent plastic template on the radar screen and moving it to the chart to fix a position.[26]

Another special technique, known as the Franklin Continuous Radar Plot Technique, involves drawing the path a radar object should follow on the radar display if the ship stays on its planned course.[27] During the transit, the navigator can check that the ship is on track by checking that the pip lies on the drawn line.[27]

Satellite navigation

Global Navigation Satellite System or GNSS is the term for satellite navigation systems that provide positioning with global coverage. A GNSS allow small electronic receivers to determine their location (longitude, latitude, and altitude) to within a few metres using time signals transmitted along a line of sight by radio from satellites. Receivers on the ground with a fixed position can also be used to calculate the precise time as a reference for scientific experiments.

As of October 2011, only the United States NAVSTAR Global Positioning System (GPS) and the Russian GLONASS are fully globally operational GNSSs. The European Union's Galileo positioning system is a next generation GNSS in the initial deployment phase, scheduled to be operational by 2013. China has indicated it may expand its regional Beidou navigation system into a global system.

More than two dozen GPS satellites are in medium Earth orbit, transmitting signals allowing GPS receivers to determine the receiver's location, speed and direction.

Since the first experimental satellite was launched in 1978, GPS has become an indispensable aid to navigation around the world, and an important tool for map-making and land surveying. GPS also provides a precise time reference used in many applications including scientific study of earthquakes, and synchronization of telecommunications networks.

Developed by the United States Department of Defense, GPS is officially named NAVSTAR GPS (NAVigation Satellite Timing And Ranging Global Positioning System). The satellite constellation is managed by the United States Air Force 50th Space Wing. The cost of maintaining the system is approximately US$750 million per year,[28] including the replacement of aging satellites, and research and development. Despite this fact, GPS is free for civilian use as a public good.

Navigation processes

Day's work in navigation

The Day's work in navigation is a minimal set of tasks consistent with prudent navigation. The definition will vary on military and civilian vessels, and from ship to ship, but takes a form resembling:[29]

1. Maintain continuous dead reckoning plot.
2. Take two or more star observations at morning twilight for a celestial fix (prudent to observe 6 stars).
3. Morning sun observation. Can be taken on or near prime vertical for longitude, or at any time for a line of position.
4. Determine compass error by azimuth observation of the sun.
5. Computation of the interval to noon, watch time of local apparent noon, and constants for meridian or ex-meridian sights.
6. Noontime meridian or ex-meridian observation of the sun for noon latitude line. Running fix or cross with Venus line for noon fix.
7. Noontime determination the day's run and day's set and drift.
8. At least one afternoon sun line, in case the stars are not visible at twilight.
9. Determine compass error by azimuth observation of the sun.
10. Take two or more star observations at evening twilight for a celestial fix (prudent to observe 6 stars).

Passage planning

Poor passage planning and deviation from the plan can lead to groundings, ship damage and cargo loss.

Passage planning or voyage planning is a procedure to develop a complete description of vessel's voyage from start to finish. The plan includes leaving the dock and harbor area, the enroute portion of a voyage, approaching the destination, and mooring. According to international law, a vessel's captain is legally responsible for passage planning,[] however on larger vessels, the task will be delegated to the ship's navigator.[]

Studies show that human error is a factor in 80 percent of navigational accidents and that in many cases the human making the error had access to information that could have prevented the accident.[] The practice of voyage planning has evolved from penciling lines on nautical charts to a process of risk management.[]

Passage planning consists of four stages: appraisal, planning, execution, and monitoring,[] which are specified in *International Maritime Organization Resolution A.893(21), Guidelines For Voyage Planning,*[] and these guidelines are reflected in the local laws of IMO signatory countries (for example, Title 33 of the U.S. Code of Federal Regulations), and a number of professional books or publications. There are some fifty elements of a comprehensive passage plan depending on the size and type of vessel.

The appraisal stage deals with the collection of information relevant to the proposed voyage as well as ascertaining risks and assessing the key features of the voyage. In the next stage, the written plan is created. The third stage is the execution of the finalised voyage plan, taking into account any special circumstances which may arise such as changes in the weather, which may require the plan to be reviewed or altered. The final stage of passage planning consists of monitoring the vessel's progress in relation to the plan and responding to deviations and unforeseen circumstances.

Integrated bridge systems

Electronic integrated bridge concepts are driving future navigation system planning.[18] Integrated systems take inputs from various ship sensors, electronically display positioning information, and provide control signals required to maintain a vessel on a preset course.[18] The navigator becomes a system manager, choosing system presets, interpreting system output, and monitoring vessel response.[18]

Notes

[1] Bowditch, 2003:799.
[2] *The Ty Pros Companion to Ships and the Sea*, Peter Kemp ed., 1976 ISBN 0-586-08308-1
[4] http://www.ancruzeiros.pt/anci-astrolabio.html
[5] See es:Martín Cortés de Albacar for the Spanish Wikipedia biography
[6] Swanick, Lois Ann. *An Analysis Of Navigational Instruments In The Age Of Exploration: 15th Century To Mid-17th century*, MA Thesis, Texas A&M University, December 2005
[7] Online Etymology Dictionary (http://www.etymonline.com/index.php?search=&searchmode=none)
[8] Bowditch, 2003:4.
[13] Lecky, Squire, *Wrinkles in Practical Navigation*
[14] Maloney, 2003:615.
[15] Maloney, 2003:614
[16] Maloney, 2003:618.
[17] Maloney, 2003:622.
[18] Bowditch, 2002:1.
[19] Bowditch, 2002:105.
[20] Bowditch, 2002:269.
[21] http://www.jproc.ca/hyperbolic/omega.html
[22] Maloney, 2003:744.
[23] Bowditch, 2002:816.
[24] National Imagery and Mapping Agency, 2001:163.
[25] National Imagery and Mapping Agency, 2001:169.
[26] National Imagery and Mapping Agency, 2001:164.
[27] National Imagery and Mapping Agency, 2001:182.
[28] GPS Overview from the NAVSTAR Joint Program Office (http://gps.losangeles.af.mil/jpo/gpsoverview.htm). Accessed December 15, 2006.
[29] Turpin and McEwen, 1980:6-18.

References

- Bowditch, Nathaniel (2002). *The American Practical Navigator* (http://www.irbs.com/bowditch/). Bethesda, MD: National Imagery and Mapping Agency. ISBN 0-939837-54-4.
- Cutler, Thomas J. (December 2003). *Dutton's Nautical Navigation* (15th ed.). Annapolis, MD: Naval Institute Press. ISBN 978-1-55750-248-3.
- Department of the Air Force (March 2001). *Air Navigation* (http://www.e-publishing.af.mil/pubfiles/af/11/afpam11-216/afpam11-216.pdf) (PDF). Department of the Air Force. Retrieved 2007-04-17.
- Great Britain Ministry of Defence (Navy) (1995). *Admiralty Manual of Seamanship*. The Stationery Office. ISBN 0-11-772696-6.
- Bernhard Hofmann-Wellenhof; K. Legat; M. Wieser (2003). *Navigation: principles of positioning and guidance* (http://books.google.com/books?id=losWr9UDRasC). Springer. ISBN 978-3-211-00828-7. Retrieved 7 February 2012.
- Maloney, Elbert S. (December 2003). *Chapman Piloting and Seamanship* (64th ed.). New York, NY: Hearst Communications Inc. ISBN [[Special:BookSources/1-58816-098-0 1-58816-098-0 [[Category:Articles with invalid ISBNs]] Check `|isbn=` value (help).
- National Imagery and Mapping Agency (2001). *Publication 1310: Radar Navigation and Maneuvering Board Manual* (http://www.nga.mil/portal/site/maritime/) (PDF) (7th edition ed.). Bethesda, MD: U.S. Government

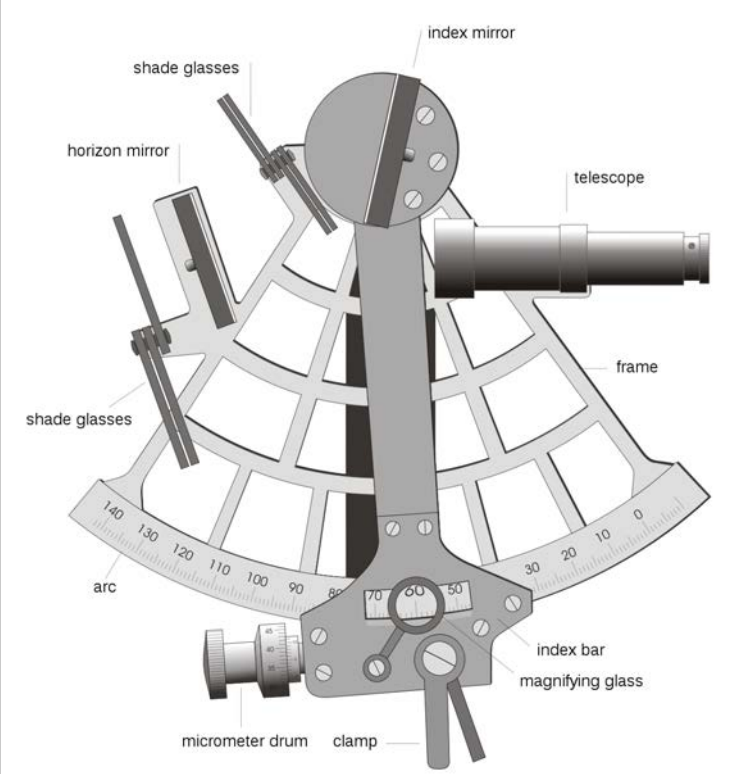
Printing Office.
- Turpin, Edward A.; McEwen, William A. (1980). *Merchant Marine Officers' Handbook* (4th ed.). Centreville, MD: Cornell Maritime Press. ISBN 0-87033-056-X.
- Encyclopædia Britannica (1911). "Navigation" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **19** (11th edition ed.). Retrieved 2007-04-17.
- Encyclopædia Britannica (1911). "Pytheas" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **22** (11th edition ed.). Retrieved 2007-04-17.

External links

- The Navlist community: devoted to the history, practice, and preservation of traditional navigation techniques (http://www.fer3.com/NavList/)
- General Concepts about Marine Navigation (http://www.globmaritime.com/martech/marine-navigation/general-concepts/)
- *Lectures in Navigation* (http://www.gutenberg.org/etext/27642) by Ernest Gallaudet Draper
- *Navigasyon* (http://www.navigasyon.net) Navigasyon
- Navigation (http://www.wildernessmanuals.com/manual_6/chpt_2/index.html) - U.S. Army Manual
- Bowditch Online (http://fer3.com/arc/imgx/Bowditch-American-Practical-Navigator-2002-(2004).pdf) - complete online edition of the 2002 edition of "Bowditch," *The American Practical Navigator*
- Navigational algorithms (http://sites.google.com/site/navigationalalgorithms/)
- Precision navigation tutorial (http://gge.unb.ca/Research/GRL/GeodesyGroup/tutorial/precision_navigation.htm) at University of New Brunswick
- How to navigate with less than a compass or GPS (http://alsworld.topcities.com/bwgg/index.html)
- LOCUS (http://www.locus.org.uk/) research project about mobile navigation using a digital compass and a GPS.
- IACS Unified Requirement N: Navigation (http://www.iacs.org.uk/document/public/Publications/Unified_requirements/PDF/UR_N_pdf156.PDF)
- Glossary of Nautical Terms (http://www.camelot-sailing.com/glossary.html)
- SOLAS requirement (http://www.nauticpal.com/content/solas-amendments-additional-bridge-equipment) for Bridge Navigational Watch Alarm System (BNWAS) and for an Electronic Chart Display and Information System (ECDIS)

Celestial navigation

Celestial navigation, also known as **astronavigation**, is a position fixing technique that has evolved over several thousand years to help sailors cross oceans without having to rely on estimated calculations, or dead reckoning, to know their position. Celestial navigation uses "sights," or angular measurements taken between a celestial body (the sun, the moon, a planet or a star) and the visible horizon. The sun is most commonly used, but navigators can also use the moon, a planet or one of 57 navigational stars whose coordinates are tabulated in the Nautical Almanac and Air Almanacs.



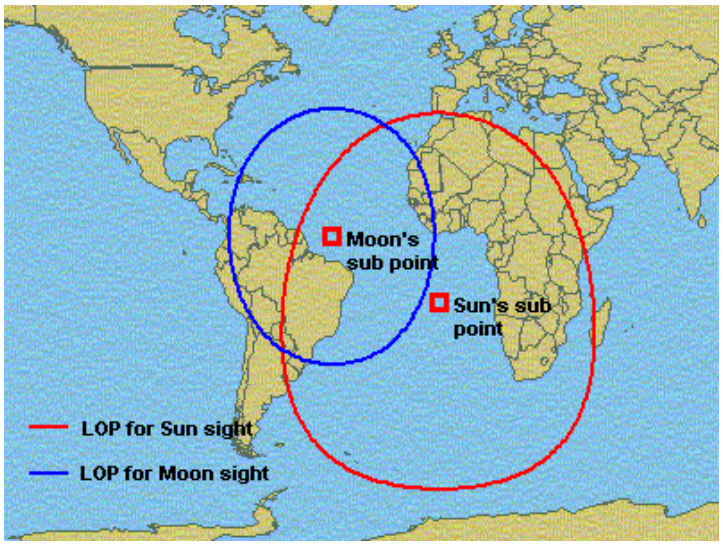
A Sextant

Celestial navigation is the use of angular measurements (sights) between celestial bodies and the visible horizon to locate one's position on the globe, on land as well as at sea. At a given time, any celestial body is located directly over one point on the Earth's surface. The latitude and longitude of that point is known as the celestial body's geographic position (GP), the location of which can be determined from tables in the Nautical or Air Almanac for that year.

The measured angle between the celestial body and the visible horizon is directly related to the distance between the celestial body's GP and the observer's position. After some computations, referred to as "sight reduction," this measurement is used to plot a line of position (LOP) on a navigational chart or plotting work sheet, the observer's position being somewhere on that line. (The LOP is actually a short segment of a very large circle on the earth which surrounds the GP of the observed celestial body. An observer located anywhere on the circumference of this circle on the earth, measuring the angle of the same celestial body above the horizon at that instant of time, would observe that body to be at the same angle above the horizon.) Sights on two celestial bodies give two such lines on the chart, intersecting at the observer's position. That premise is the basis for the most commonly used method of celestial navigation, and is referred to as the "Altitude-Intercept Method."

There are several other methods of celestial navigation which will also provide position finding using sextant observations, such as the "Noon Sight", and the more archaic "Lunar Distance" method. Joshua Slocum used the Lunar Distance method during the first ever recorded single-handed circumnavigation of the world. Unlike the Altitude-Intercept Method, the noon sight and lunar distance methods do not require accurate knowledge of time. The altitude-intercept method of celestial navigation requires that the observer know exact Greenwich Mean Time (GMT) at the moment of his observation of the celestial body, to the second.

Example

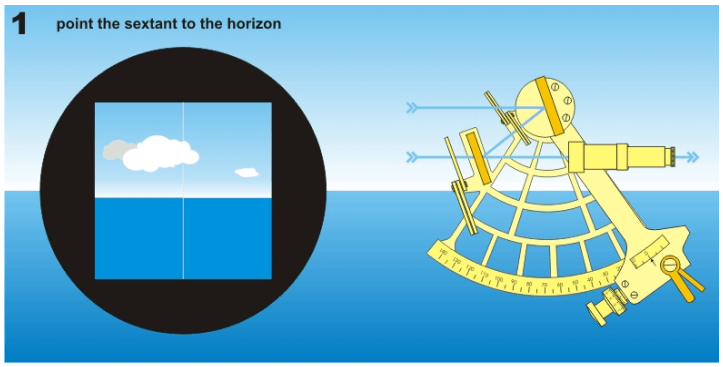


An example illustrating the concept behind the intercept method for determining one's position is shown to the right. (Two other common methods for determining one's position using celestial navigation are the longitude by chronometer and ex-meridian methods.) In the image to the right, the two circles on the map represent lines of position for the Sun and Moon at 1200 GMT on October 29, 2005. At this time, a navigator on a ship at sea measured the Moon to be 56 degrees above the horizon using a sextant. Ten minutes later, the Sun was observed to be 40 degrees above the horizon. Lines of position were then calculated and plotted for each of these observations. Since both the Sun and Moon were observed at their respective angles from the same location, the navigator would have to be located at one of the two locations where the circles cross.

In this case the navigator is either located on the Atlantic Ocean, about 350 nautical miles (650 km) west of Madeira, or in South America, about 90 nautical miles (170 km) southwest of Asunción, Paraguay. In most cases, determining which of the two intersections is the correct one is obvious to the observer because they are often thousands of miles apart. As it is unlikely that the ship is sailing across South America, the position in the Atlantic is the correct one. Note that the lines of position in the figure are distorted because of the map's projection; they would be circular if plotted on a globe.

An observer in the Chaco point would see the Moon at the left of the Sun, and an observer in the Madeira point would see the Moon at the right of the Sun, and that whoever measured the two heights was likely to observe also this one bit of information.

Angular measurement



Using a marine sextant to measure the altitude of the sun above the horizon

Accurate angle measurement evolved over the years. One simple method is to hold the hand above the horizon with your arm stretched out. The width of the little finger is an angle just over 1.5 degrees elevation at extended arms length and can be used to estimate the elevation of the sun from the horizon plane and therefore estimate the time till sunset. The need for more accurate measurements led to the development of a number of increasingly accurate instruments, including the kamal, astrolabe, octant and sextant. The sextant and octant are most accurate because they measure angles from the horizon, eliminating errors caused by the placement of an instrument's pointers, and because their dual mirror system cancels relative motions of the instrument, showing a steady view of the object and horizon.

Navigators measure distance on the globe in degrees, arcminutes and arcseconds. A nautical mile is defined as 1852 meters, but is also (not accidentally) one minute of angle along a meridian on the Earth. Sextants can be read accurately to within 0.2 arcminutes. So the observer's position can be determined within (theoretically) 0.2 miles, about 400 yards (370 m). Most ocean navigators, shooting from a moving platform, can achieve a practical accuracy of 1.5 miles (2.8 km), enough to navigate safely when out of sight of land.

Practical navigation

Practical celestial navigation usually requires a marine chronometer to measure time, a sextant to measure the angles, an almanac giving schedules of the coordinates of celestial objects, a set of sight reduction tables to help perform the height and azimuth computations, and a chart of the region. With sight reduction tables, the only calculations required are addition and subtraction. Small handheld computers, laptops and even scientific calculators enable modern navigators to "reduce" sextant sights in minutes, by automating all the calculation and/or data lookup steps. Most people can master simpler celestial navigation procedures after a day or two of instruction and practice, even using manual calculation methods.

Modern practical navigators usually use celestial navigation in combination with satellite navigation to correct a dead reckoning track, that is, a course estimated from a vessel's position, course and speed. Using multiple methods helps the navigator detect errors, and simplifies procedures. When used this way, a navigator will from time to time measure the sun's altitude with a sextant, then compare that with a precalculated altitude based on the exact time and estimated position of the observation. On the chart, one will use the straight edge of a plotter to mark each position line. If the position line shows one to be more than a few miles from the estimated position, one may take more observations to restart the dead-reckoning track.

In the event of equipment or electrical failure, one can get to a port by simply taking sun lines a few times a day and advancing them by dead reckoning to get a crude running fix.

Latitude

Latitude was measured in the past either at noon (the "noon sight") or from Polaris, the north star (assuming it is sufficiently visible above the horizon, which it is not in the Southern Hemisphere). Polaris always stays within 1 degree of the celestial north pole. If a navigator measures the angle to Polaris and finds it to be 10 degrees from the horizon, then he is about 10 degrees north of the equator. Angles are measured from the horizon because locating the point directly overhead, the zenith, is difficult. When haze obscures the horizon, navigators use artificial horizons, which are bubble levels reflected into a sextant.

Latitude can also be determined by the direction in which the stars travel over time. If the stars rise out of the east and travel straight up you are at the equator, but if they drift south you are to the north of the equator. The same is true of the day-to-day drift of the stars due to the movement of the Earth in orbit around the Sun; each day a star will drift approximately one degree. In either case if the drift can be measured accurately, simple trigonometry will reveal the latitude.

Longitude

Longitude can be measured in the same way. If one can accurately measure the angle to Polaris, a similar measurement to a star near the eastern or western horizons will provide the longitude. The problem is that the Earth turns 15 degrees per hour, making such measurements dependent on time. A measure a few minutes before or after the same measure the day before creates serious navigation errors. Before good chronometers were available, longitude measurements were based on the transit of the moon, or the positions of the moons of Jupiter. For the most part, these were too difficult to be used by anyone except professional astronomers. The invention of the modern chronometer by John Harrison in 1761 vastly simplified longitudinal calculation.

The longitude problem took centuries to solve and was dependent on the construction of a non-pendulum clock (as pendulum clocks cannot function accurately on a tilting ship, or indeed a moving vehicle of any kind). Two useful methods evolved during the 18th century and are still practised today: lunar distance, which does not involve the use of a chronometer, and use of an accurate timepiece or chronometer.

Presently, lay person calculations of longitude can be made by noting the exact local time (leaving out any reference for Daylight Savings Time) when the sun is at its highest point in the sky. The calculation of noon can be made more easily and accurately with a small, exactly vertical rod driven into level ground—take the time reading when the shadow is pointing due north (in the northern hemisphere). Then take your local time reading and subtract it from GMT (Greenwich Mean Time) or the time in east London. For example, a noon reading (1200 hours) near Central Canada or the U.S.A. would occur at approximately 6 pm (1800 hours) in London. The six hour differential is 1/4 of a 24 hour day, or 90 degrees of a 360 degree circle (the Earth). The calculation can also be made by taking the number of hours (use decimals for fractions of an hour multiplied by 15, the number of degrees in one hour). Either way, you can demonstrate that much of central USA or Canada is at or near 90 degrees West Longitude. Eastern longitudes can be determined by adding the local time to GMT, with similar calculations.

Lunar distance

The older method, called "**lunar distances**", was refined in the 18th century. It is only used today by sextant hobbyists and historians, but the method is theoretically sound, and can be used when a timepiece is not available or its accuracy is suspect during a long sea voyage. The navigator precisely measures the angle between the moon and the sun, or between the moon and one of several stars near the ecliptic. The angle naturally will depend on the navigator's position (which he doesn't know) but he can still hope to correct the angle well enough to use the tables that give the corresponding angle as viewed from the center of the earth at a given Greenwich time. The navigator would thumb through the almanac to find the angle he measured, and thus know the time at Greenwich. Modern handheld and laptop calculators can perform the calculation in minutes, allowing the navigator to use other celestial bodies than the old nine. Knowing Greenwich time, the navigator can work out his longitude.

Use of time

The considerably more popular method was (and still is) to use an accurate timepiece to directly measure the time of a sextant sight. The need for accurate navigation led to the development of progressively more accurate chronometers in the 18th century. (See John Harrison) Today, time is measured with a chronometer, a quartz watch, a shortwave radio time signal broadcast from an atomic clock, or the time displayed on a GPS. A quartz wristwatch normally keeps time within a half-second per day. If it is worn constantly, keeping it near body heat, its rate of drift can be measured with the radio, and by compensating for this drift, a navigator can keep time to better than a second per month. Traditionally, a navigator checked his chronometer from his sextant, at a geographic marker surveyed by a professional astronomer. This is now a rare skill, and most harbour masters cannot locate their harbour's marker.

Traditionally, three chronometers were kept in gimbals in a dry room near the centre of the ship. They were used to set a watch for the actual sight, so that no chronometers were ever exposed to the wind and salt water on deck. Winding and comparing the chronometers was a crucial duty of the navigator. Even today, it is still logged daily in the ship's deck log and reported to the Captain prior to *eight bells* on the forenoon watch (shipboard noon). Navigators also set the ship's clocks and calendar.

Modern celestial navigation

The celestial line of position concept was discovered in 1837 by Thomas Hubbard Sumner when, after one observation he computed and plotted his longitude at more than one trial latitude in his vicinity – and noticed that the positions lay along a line. Using this method with two bodies, navigators were finally able to cross two position lines and obtain their position – in effect determining both latitude and longitude. Later in the 19th century came the development of the modern (Marcq St. Hilaire) intercept method; with this method the body height and azimuth are calculated for a convenient trial position, and compared with the observed height. The difference in arcminutes is the nautical mile "intercept" distance that the position line needs to be shifted toward or away from the direction of the body's subpoint. (The intercept method uses the concept illustrated in the example in the “How it works” section above.) Two other methods of reducing sights are the longitude by chronometer and the ex-meridian method.

While celestial navigation is becoming increasingly redundant with the advent of inexpensive and highly accurate satellite navigation receivers (GPS), it was used extensively in aviation until the 1960s, and marine navigation until quite recently. But since a prudent mariner never relies on any sole means of fixing his position, many national maritime authorities still require deck officers to show knowledge of celestial navigation in examinations, primarily as a back-up for electronic navigation. One of the most common current usages of celestial navigation aboard large merchant vessels is for compass calibration and error checking at sea when no terrestrial references are available.

The U.S. Air Force and U.S. Navy continued instructing military aviators on its use until 1997, because:

- it can be used independently of ground aids
- has global coverage
- cannot be jammed (although it can be obscured by clouds)
- does not give off any signals that could be detected by an enemy [1]

The US Naval Academy announced that it was discontinuing its course on celestial navigation, considered to be one of its more demanding courses, from the formal curriculum in the spring of 1998 stating that a sextant is accurate to a three-mile (5 km) radius, while a satellite-linked computer can pinpoint a ship within 60 feet (18 m). Presently, midshipmen continue to learn to use the sextant, but instead of performing a tedious 22-step mathematical calculation to plot a ship's course, midshipmen feed the raw data into a computer.[2] At another federal service academy, the US Merchant Marine Academy, students are still taught courses in celestial navigation, as it is required to pass the US Coast Guard License Exam.

Likewise, celestial navigation was used in commercial aviation up until the early part of the jet age; it was only phased out in the 1960s with the advent of inertial navigation systems.

Celestial navigation continues to be taught to cadets during their training in the Merchant Navy and remains as a requirement for their certificate of competency.

A variation on terrestrial celestial navigation was used to help orient the Apollo spacecraft en route to and from the Moon. To this day, space missions, such as the Mars Exploration Rover use star trackers to determine the attitude of the spacecraft.

As early as the mid-1960s, advanced electronic and computer systems had evolved enabling navigators to obtain automated celestial sight fixes. These systems were used aboard both ships as well as US Air Force aircraft, and were highly accurate, able to lock onto up to 11 stars (even in daytime) and resolve the craft's position to less than 300 feet (91 m). The SR-71 high-speed reconnaissance aircraft was one example of an aircraft that used automated celestial navigation. These rare systems were expensive, however, and the few that remain in use today are regarded as backups to more reliable satellite positioning systems.

Celestial navigation continues to be used by private yachtsmen, and particularly by long-distance cruising yachts around the world. For small cruising boat crews, celestial navigation is generally considered an essential skill when venturing beyond visual range of land. Although GPS (Global Positioning System) technology is reliable, offshore yachtsmen use celestial navigation as either a primary navigational tool or as a backup.

Intercontinental ballistic missiles use celestial navigation to check and correct their course (initially set using internal gyroscopes) while outside the Earth's atmosphere. The immunity to jamming signals is the main driver behind this apparently archaic technique.

Celestial navigation trainer

Celestial navigation trainers combine a simple flight simulator with a planetarium in order to train aircraft crews in celestial navigation.

An early example is the Link Celestial Navigation Trainer, used in the Second World War.[3][4] Housed in a 45 feet (14 m) high building, it featured a cockpit which accommodated a whole bomber crew (pilot, navigator and bombardier). The cockpit offered a full array of instruments which the pilot used to fly the simulated aeroplane. Fixed to a dome above the cockpit was an arrangement of lights, some collimated, simulating constellations from which the navigator determined the plane's position. The dome's movement simulated the changing positions of the stars with the passage of time and the movement of the plane around the earth. The navigator also received simulated radio signals from various positions on the ground.

Below the cockpit moved "terrain plates" – large, movable aerial photographs of the land below, which gave the crew the impression of flight and enabled the bomber to practise lining up bombing targets.

A team of operators sat at a control booth on the ground below the machine, from which they could simulate weather conditions such as wind or cloud. This team also tracked the aeroplane's position by moving a "crab" (a marker) on a paper map.

The Link Celestial Navigation Trainer was developed in response to a request made by the Royal Air Force (RAF) in 1939. The RAF ordered 60 of these machines, and the first one was built in 1941. The RAF used only a few of these, leasing the rest back to the U.S., where eventually hundreds were in use.

References

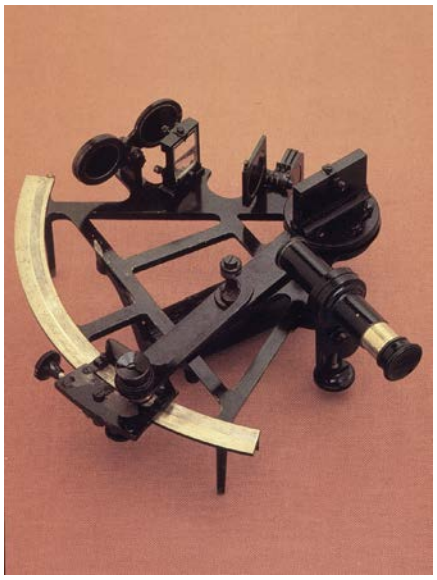
[1] U.S. Air Force Pamphlet (AFPAM) 11-216, Chapters 8-13

[2] Navy Cadets Won't Discard Their Sextants (http://query.nytimes.com/gst/fullpage.html?res=9504EED61038F93AA15756C0A96E958260&n=Top/Reference/Times Topics/Organizations/U/United States Naval Academy), The New York Times By DAVID W. CHEN Published: May 29, 1998

External links

- Celestial Navigation Net (http://www.celestialnavigation.net)
- Table of the 57 navigational stars with apparent magnitudes and celestial coordinates (http://www.angelfire.com/nt/navtrig/F1.html)
- John Harrison and the Longitude problem (http://www.nmm.ac.uk/server/show/conWebDoc.355) at the National Maritime Museum, Greenwich, England
- Calculating Lunar Distances (http://www.clockwk.com/lunars/easylun.html)
- Navigational Algorithms (http://sites.google.com/site/navigationalalgorithms/)
- Backbearing.com (http://www.backbearing.com/index.html) Almanac, Sight Reduction Tables and more.
- Navigation Spreadsheets (http://www.navigation-spreadsheets.com/) Free Excel spreadsheets including almanac data, sight reduction calculations, and much more.

Sextant



A sextant

A **sextant** is an instrument used to measure the angle between any two visible objects. Its primary use is to determine the angle between a celestial object and the horizon which is known as the object's *altitude*. Making this measurement is known as *sighting* the object, *shooting* the object, or *taking a sight* and it is an essential part of celestial navigation. The angle, and the time when it was measured, can be used to calculate a position line on a nautical or aeronautical chart. Common uses of the sextant include sighting the sun at solar noon and sighting Polaris at night, to find one's latitude (in northern latitudes). Sighting the height of a landmark can give a measure of *distance off* and, held horizontally, a sextant can measure angles between objects for a position on a chart.[1] A sextant can also be used to measure the lunar distance between the moon and another celestial object (e.g., star, planet) in order to determine Greenwich time which is important because it can then be used to determine the longitude.

The scale of a sextant has a length of ⅙ of a turn (60°); hence the sextant's name (*sextāns, -antis* is the Latin word for "one sixth"). An octant is a similar device with a shorter scale (⅛ turn, or 45°), whereas a quintant (⅕ turn, or 72°) and a quadrant (¼ turn, or 90°) have longer scales.

Sir Isaac Newton (1643–1727) invented the principle of the doubly reflecting navigation instrument (a reflecting quadrant—see Octant (instrument)), but never published it. Two men independently developed the octant around 1730: John Hadley (1682–1744), an English mathematician, and Thomas Godfrey (1704–1749), a glazier in Philadelphia. John Bird made the first sextant in 1757. The octant and later the sextant, replaced the Davis quadrant as the main instrument for navigation.

Navigational sextants

This section discusses navigators' sextants. Most of what is said about these specific sextants applies equally to other types of sextants. Navigators' sextants were primarily used for celestial navigation.

Man using a sextant

U.S. Navy officer using a sextant

Advantages

Like the Davis quadrant (also called backstaff), the sextant allows celestial objects to be measured relative to the horizon, rather than relative to the instrument. This allows excellent precision. However, unlike the backstaff, the sextant allows direct observations of stars. This permits the use of the sextant at night when a backstaff is difficult to use. For solar observations, filters allow direct observation of the sun.

Since the measurement is relative to the horizon, the measuring pointer is a beam of light that reaches to the horizon. The measurement is thus limited by the angular accuracy of the instrument and not the sine error of the length of an alidade, as it is in a mariner's astrolabe or similar older instrument.

A sextant does not require a completely steady aim, because it measures a relative angle. For example, when a sextant is used on a moving ship, the image of both horizon and celestial object will move around in the field of view. However, the relative position of the two images will remain steady, and as long as the user can determine when the celestial object touches the horizon the accuracy of the measurement will remain high compared to the magnitude of the movement.

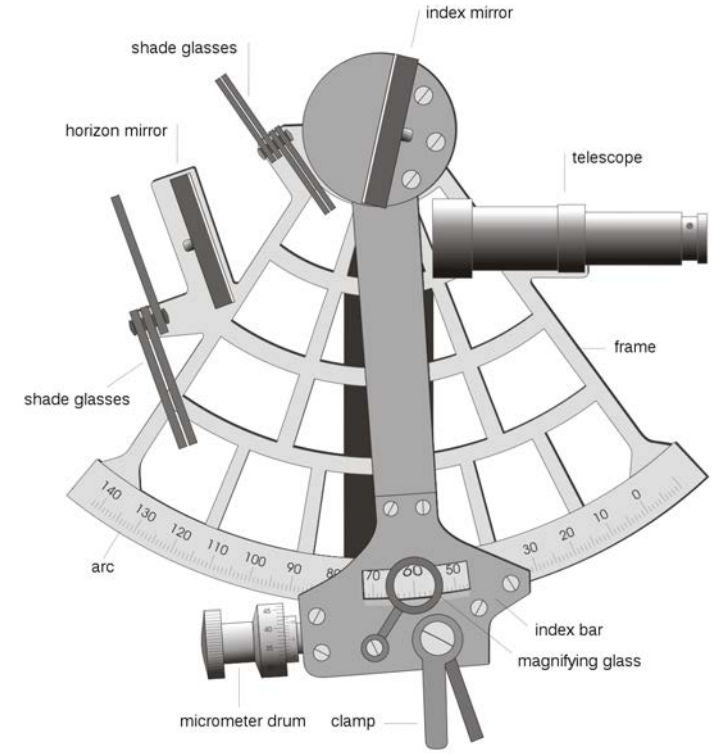
The sextant is not dependent upon electricity (unlike many forms of modern navigation) or anything human-controlled (like GPS satellites). For these reasons, it is considered an eminently practical back-up navigation tool for ships.

Anatomy of a sextant

The *index arm* moves the *index mirror*. The *indicator* points at the *arc* to show the measurement. The body ties everything together.

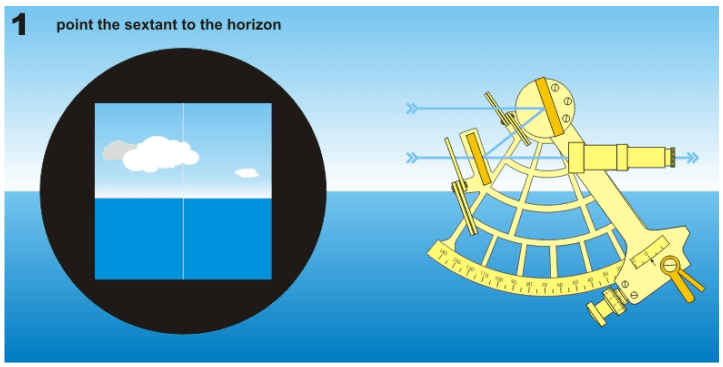
There are two types of sextants. Both types give good results, and the choice between them is personal.

Traditional sextants have a half-horizon mirror. It divides the field of view in two. On one side, there is a view of the horizon; on the other side, a view of the celestial object. The advantage of this type is that both the horizon and celestial object are bright and as clear as possible. This is superior at night and in haze, when the horizon can be difficult to see. However, one has to sweep the celestial object to ensure that the lowest limb of the celestial object touches the horizon.



Marine Sextant

Whole-horizon sextants use a half-silvered horizon mirror to provide a full view of the horizon. This makes it easy to see when the bottom limb of a celestial object touches the horizon. Since most sights are of the sun or moon, and haze is rare without overcast, the low-light advantages of the half-horizon mirror are rarely important in practice.



Using the sextant to measure the altitude of the Sun above the horizon

In both types, larger mirrors give a larger field of view, and thus make it easier to find a celestial object. Modern sextants often have 5 cm or larger mirrors, while 19th century sextants rarely had a mirror larger than 2.5 cm (one inch). In large part, this is because precision flat mirrors have grown less expensive to manufacture and to silver.

An artificial horizon is useful when the horizon is invisible. This occurs in fog, on moonless nights, in a calm, when sighting through a window or on land surrounded by trees or buildings. Professional sextants can mount an artificial horizon in place of the horizon-mirror assembly. An artificial horizon is usually a mirror that views a fluid-filled tube with a bubble.

Most sextants also have filters for use when viewing the sun and reducing the effects of haze.

Most sextants mount a 1 or 3 power monocular for viewing. Many users prefer a simple sighting tube, which has a wider, brighter field of view and is easier to use at night. Some navigators mount a light-amplifying monocular to help see the horizon on moonless nights. Others prefer to use a lit artificial horizon.

Professional sextants use a click-stop degree measure and a worm adjustment that reads to a minute, 1/60 of a degree. Most sextants also include a vernier on the worm dial that reads to 0.2 minute. Since 1 minute of error is

about a nautical mile, the best possible accuracy of celestial navigation is about 0.1 nautical miles (200 m). At sea, results within several nautical miles, well within visual range, are acceptable. A highly-skilled and experienced navigator can determine position to an accuracy of about 0.25-nautical-mile (460 m).[2]

A change in temperature can warp the arc, creating inaccuracies. Many navigators purchase weatherproof cases so that their sextant can be placed outside the cabin to come to equilibrium with outside temperatures. The standard frame designs (see illustration) are supposed to equalise differential angular error from temperature changes. The handle is separated from the arc and frame so that body heat does not warp the frame. Sextants for tropical use are often painted white to reflect sunlight and remain relatively cool. High-precision sextants have an invar (a special low-expansion steel) frame and arc. Some scientific sextants have been constructed of quartz or ceramics with even lower expansions. Many commercial sextants use low expansion brass or aluminium. Brass is lower-expansion than aluminium, but aluminium sextants are lighter and less tiring to use. Some say they are more accurate because one's hand trembles less.

Aircraft sextants are now out of production, but had special features. Most had artificial horizons to permit taking a sight through a flush overhead window. Some also had mechanical averagers to make hundreds of measurements per sight for compensation of random accelerations in the artificial horizon's fluid. Older aircraft sextants had two visual paths, one standard and the other designed for use in open-cockpit aircraft that let one view from directly over the sextant in one's lap. More modern aircraft sextants were periscopic with only a small projection above the fuselage. With these, the navigator pre-computed his sight and then noted the difference in observed versus predicted height of the body to determine his position.

After a sight is taken, it is reduced to a position by following any of several mathematical procedures. The simplest sight reduction is to draw the equal-elevation circle of the sighted celestial object on a globe. The intersection of that circle with a dead-reckoning track, or another sighting gives a more precise location.

Taking a sight

To *sight* (or *measure*) the angle between the sun, a star, or a planet, and the horizon the 'star telescope' should be fitted to the sextant. The horizon should also be visible. On a vessel at sea, this is usually no problem; on misty days, sighting from a low height above the water may give a more definite, better horizon. The sextant is removed from its box and held by the handle in the right hand, without ever touching the arc with the fingers.[]

For a sun sight, the shades of the sextant overcome glare. One method of starting is to use both index mirror and horizon mirror shades, of sufficient darkness that the sun appears through either as a solid disk and does not hurt the eyes. By setting the index bar to zero, the sun can be viewed through the telescope. Releasing the index bar (either by releasing a clamping screw, or on modern instruments, using the quick-release button), the image of the sun can be brought down to about the level of the horizon. It is necessary to flip back the horizon mirror shade to be able to see the horizon, and then the fine adjustment screw on the end of the index bar is turned until the bottom curve (the *lower limb*) of the sun just touches the horizon. 'Swinging' the sextant about the axis of the telescope ensures that the reading is being taken with the instrument held vertically. The angle of the sight is then read from the scale on the arc, making use of the micrometer or vernier scale provided. The exact time of the sight must also be noted simultaneously, and the height of the eye above sea-level recorded.[]

An alternative method is to estimate the current altitude (angle) of the sun from navigation tables, then set the index bar to that angle on the arc, apply suitable shades only to the index mirror, and point the instrument directly at the horizon, sweeping it from side to side until a flash of the sun's rays are seen in the telescope. Fine adjustments are then made as above. This method is less likely to be successful for sighting stars and planets.[]

Star and planet sights are normally taken during nautical twilight at dawn or dusk, while both the heavenly bodies and the sea horizon are visible. There is no need to use shades or to distinguish the lower limb as the body appears as a mere point in the telescope. The moon can be sighted, but it appears to move very fast, appears to have different sizes at different times, and sometimes only the lower or upper limb can be distinguished due to its phase.[]

Sextants can be used very accurately to measure other visible angles, for example between one heavenly body and another and between landmarks ashore. Used horizontally, a sextant can measure the apparent angle between two landmarks such as a lighthouse and a church spire, which can then be used to find the distance *off* or out to sea (provided the distance between the two landmarks is known). Used vertically, a measurement of the angle between the lantern of a lighthouse of known height and the sea level at its base can also be used for distance off.[]

Adjustment

Due to the sensitivity of the instrument it is easy to knock the mirrors out of adjustment. For this reason a sextant should be checked frequently for errors and adjusted accordingly.

There are four errors that can be adjusted by the navigator and they should be removed in the following order.

Perpendicularity error

This is when the index mirror is not perpendicular to the frame of the sextant. To test for this, place the index arm at about 60° on the arc and hold the sextant horizontally with the arc away from you at arms length and look into the index mirror. The arc of the sextant should appear to continue unbroken into the mirror. If there is an error then the two views will appear to be broken. Adjust the mirror until the reflection and direct view of the arc appear to be continuous.

Side error

This occurs when the horizon glass/mirror is not perpendicular to the plane of the instrument. To test for this, first zero the index arm then observe a star through the sextant. Then rotate the tangent screw back and forth so that the reflected image passes alternately above and below the direct view. If in changing from one position to another the reflected image passes directly over the unreflected image, no side error exists. If it passes to one side, side error exists. The user can hold the sextant on its side and observe the horizon to check the sextant during the day. If there are two horizons there is side error; adjust the horizon glass/mirror until the stars merge into one image or the horizons are merged into one. Side error is generally inconsequential for observations and can be ignored or reduced to a level that is merely convenient.

Collimation error

This is when the telescope or monocular is not parallel to the plane of the sextant. To check for this you need to observe two stars 90° or more apart. Bring the two stars into coincidence either to the left or the right of the field of view. Move the sextant slightly so that the stars move to the other side of the field of view. If they separate there is collimation error.

Index error

This occurs when the index and horizon mirrors are not parallel to each other when the index arm is set to zero. To test for index error, zero the index arm and observe the horizon. If the reflected and direct image of the horizon are in line there is no index error. If one is above the other adjust the index mirror until the two horizons merge. This can be done at night with a star or with the moon.

Notes

[2] Dutton's Navigation and Piloting, 12th edition. G.D. Dunlap and H.H. Shufeldt, eds. Naval Institute Press 1972, ISBN 0-87021-163-3

References

- Bowditch, Nathaniel (2002). *The American Practical Navigator* (http://www.irbs.com/bowditch/). Bethesda, MD: National Imagery and Mapping Agency. ISBN 0-939837-54-4.
- Cutler, Thomas J. (December 2003). *Dutton's Nautical Navigation* (15th ed.). Annapolis, MD: Naval Institute Press. ISBN 978-1-55750-248-3.
- Department of the Air Force (March 2001). *Air Navigation* (http://www.e-publishing.af.mil/pubfiles/af/11/afpam11-216/afpam11-216.pdf) (PDF). Department of the Air Force. Retrieved 2007-04-17.
- Great Britain Ministry of Defence (Navy) (1995). *Admiralty Manual of Seamanship*. The Stationery Office. ISBN 0-11-772696-6.
- Encyclopædia Britannica (1911). "Navigation" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **19** (11th ed.). Retrieved 2007-04-17.
- Encyclopædia Britannica (1911). "Sextant" (http://en.wikisource.org/wiki/User:Tim_Starling/ScanSet_TIFF_demo). In Chisholm, Hugh. *Encyclopædia Britannica* **24** (11th ed.). pp. 749–751. Retrieved 2007-04-17.
- Maloney, Elbert S. (December 2003). *Chapman Piloting and Seamanship* (64th ed.). New York: Hearst Communications. ISBN [[Special:BookSources/1-58816-098-0 1-58816-098-0 [[Category:Articles with invalid ISBNs]] Check `|isbn=` value (help).

External links

- Her Majesty's Nautical Almanac Office (http://www.hmnao.com/)
- The History of HM Nautical Almanac Office (http://astro.ukho.gov.uk/nao/history/)
- Chapter 17 from the online edition of [[Nathaniel Bowditch (http://en.wikisource.org/wiki/The_American_Practical_Navigator/Chapter_17)]'s *American Practical Navigator*]
- CD-Sextant - Build your own sextant (http://www.tecepe.com.br/nav/CDSextantProject.htm) Simple do-it-yourself project.
- Lunars web site. online calculation (http://www.historicalatlas.com/lunars)
- Complete celnav theory book, including Lunars (http://www.celnav.de)

Octant (instrument)

The **octant**, also called **reflecting quadrant**, is a measuring instrument used primarily in navigation. It is a type of reflecting instrument.

Octant. This instrument, labelled *Crichton - London, Sold by J Berry, Aberdeen*, appears to have an ebony frame with ivory scale, vernier and signature plate. The index arm and mirror supports are brass. Rather than use a sighting telescope, this instrument has a sighting pinnula.

Etymology

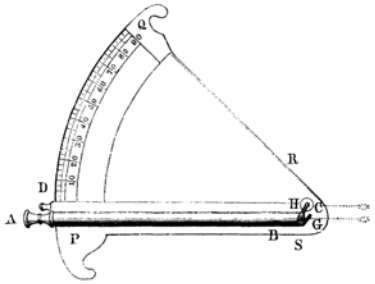
The name *octant* derives from the Latin *octans* meaning *eighth part of a circle*, because the instrument's arc is one eighth of a circle.

Reflecting quadrant derives from the instrument using mirrors to reflect the path of light to the observer and, in doing so, doubles the angle measured. This allows the instrument to use a one-eighth of a turn to measure a quarter-turn or quadrant.

Origin of the octant

Newton's reflecting quadrant

Isaac Newton's reflecting quadrant was invented around 1699.[1] A detailed description of the instrument was given to Edmond Halley, but the description was not published until after Halley's death in 1742. It is not known why Halley did not publish the information during his life, however this prevents Newton from getting the credit for the invention that is generally given to John Hadley and Thomas Godfrey.



Drawing of Newton's Reflecting Quadrant. From Memoirs of the Life, Writings, and Discoveries of Sir Isaac Newton by David Brewster, 1855A-B - sighting telescope C-D - index arm G - horizon mirror H - index mirror P-Q - graduated arc

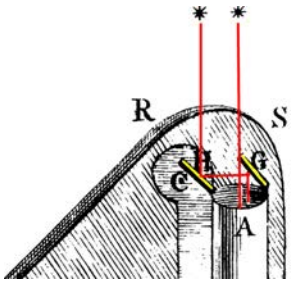
One copy of this instrument was constructed by Thomas Heath and may have been shown in Heath's shop window prior to its being published by the Royal Society in 1742.[2]

Newton's instrument used two mirrors, but they were used in an arrangement somewhat different than the two mirrors found in modern octants and sextants. The diagram on the right shows the configuration of the instrument.[3]

The 45° arc of the instrument (P-Q), was graduated with 90 divisions of a half-degree each. Each such division was subdivided into 60 parts and each part further divided into sixths. This results in the arc being marked in degrees, minutes and sixths of a minute (10 seconds). Thus the instrument could have readings interpolated to 5 seconds of arc. This fineness of graduation is only possible due to the large size of the instrument - the sighting telescope alone was three to four feet long.

A *sighting telescope* (A-B), three or four feet long, was mounted along one side of the instrument. A *horizon mirror*, was fixed at a 45° angle in front of the telescope's objective lens (G). This mirror was small enough to allow the observer to see the image in the mirror on one side and to see directly ahead on the other. The index arm (C-D) held an index mirror (H), also at 45° to the edge of the index arm. The reflective sides of the two mirrors nominally faced each other, so that the image seen in the first mirror is that reflected from the second.

With the two mirrors parallel, the index reads 0°. The view through the telescope sees directly ahead on one side and the view from the mirror G sees the same image reflected from mirror H (see detail drawing to the right). When the index arm is moved from zero to a large value, the *index mirror* reflects an image that is in a direction away from the direct line of sight. As the index arm movement increases, the line of sight for the index mirror moves toward S (to the right in the detail image). This shows a slight deficiency with this mirror arrangement. The horizon mirror will block the view of the index mirror at angles approaching 90°.



Details of the mirrors on Newton's reflecting quadrant, showing the light paths (red) through the instrument. This image is turned 90° anticlockwise relative to the one above.

The length of the sighting telescope seems remarkable, given the small size of the telescopes on modern instruments. This was likely Newton's choice of a way to reduce chromatic aberrations. Short–focal length telescopes, prior to the development of achromatic lenses, produced an objectionable degree of aberration, so much so that it could affect the perception of a star's position. Long focal lengths were the solution, and this telescope would likely have had both a long–focal length objective lens and a long–focal length eyepiece. This would decrease aberrations without excessive magnification.

The inventors of the octant

Two men independently developed the octant around 1730: John Hadley (1682–1744), an English mathematician, and Thomas Godfrey (1704–1749), a glazier in Philadelphia. While both have a legitimate and equal claim to the invention, Hadley generally gets the greater share of the credit. This reflects the central role that London and the Royal Society played in the history of scientific instruments in the eighteenth century.

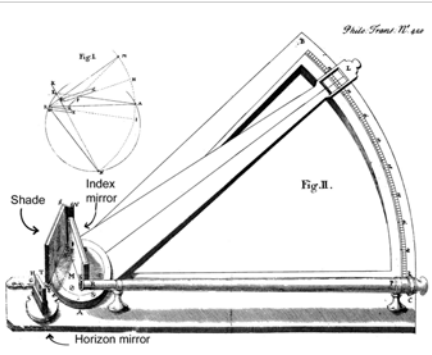
Two others who created octants during this period were Caleb Smith, an English insurance broker with a strong interest in astronomy (in 1734), and Jean-Paul Fouchy, a mathematics professor and astronomer in France (in 1732).

Hadley's versions

Hadley produced two versions of the reflecting quadrant. Only the second is well known and is the familiar octant.

Hadley's reflecting quadrant

Hadley's first reflecting quadrant was a simple device with a frame spanning a 45° arc. In the image at the right, from Hadley's article in the Philosophical Transactions of the Royal Society,[4] you can see the nature of his design. A small sighting telescope was mounted on the frame along one side. One large *index mirror* was mounted at the point of rotation of the index arm. A second, smaller *horizon mirror* was mounted on the frame in the line of sight of the telescope. The horizon mirror allows the observer to see the image of the index mirror in one half of the view and to see a distant object in the other half. A shade was mounted at the vertex of the instrument to allow one to observe a bright object. The shade pivots to allow it to move out of the way for stellar observations.



Hadley's reflecting quadrant. This instrument follows the form of Newton's reflecting quadrant from 1699

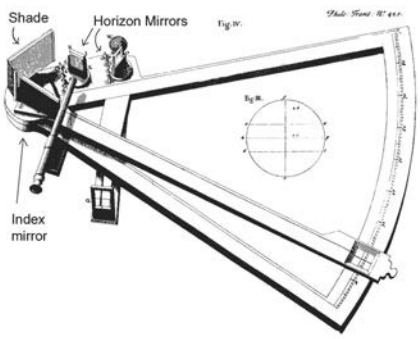
Observing through the telescope, the navigator would sight one object directly ahead. The second object would be seen by reflection in the horizon mirror. The light in the horizon mirror is reflected from the index mirror. By moving the index arm, the index mirror can be made to reveal any object up to 90° from the direct line of sight. When both objects are in the same view, aligning them together allows the navigator to measure the angular distance

between them.

Very few of the original reflecting quadrant designs were ever produced. One, constructed by Baradelle, is in the collection if the Musée de la Marine, Paris.[5]

Hadley's octant

Hadley's second design had the form familiar to modern navigators. The image to the right, also taken from his Royal Society publication,[4] shows the details.



Hadley's Octant. This is in the form familiar to those who have seen a sextant.

He placed an *index mirror* on the index arm. Two *horizon mirrors* were provided. The upper mirror, in the line of the sighting telescope, was small enough to allow the telescope to see directly ahead as well as seeing the reflected view. The reflected view was that of the light from the index mirror. As in the previous instrument, the arrangement of the mirrors allowed the observer to simultaneously see an object straight ahead and to see one reflected in the index mirror to the horizon mirror and then into the telescope. Moving the index arm allowed the navigator to see any object within 90° of the direct view.

The significant difference with this design was that the mirrors allowed the instrument to be held vertically rather than horizontally and it provided more room for configuring the mirrors without suffering from mutual interference.

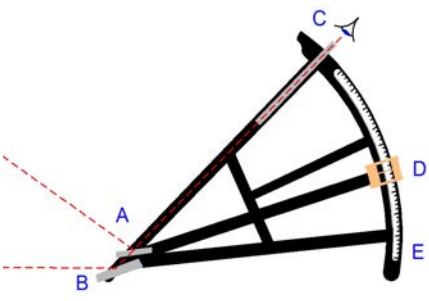
The second horizon mirror was an interesting innovation. The telescope was removable. It could be remounted so that the telescope viewed the second horizon mirror from the opposite side of the frame. By mounting the two horizon mirrors at right angles to each other and permitting the movement of the telescope, the navigator could measure angles from 0 to 90° with one horizon mirror and from 90° to 180° with the other. This made the instrument very versatile. For unknown reasons, this feature was not implemented on octants in general use.

Comparing this instrument to the photo of a typical octant at the top of the article, one can see that the only significant differences in the more modern design are:

- The location of the horizon mirror and telescope or sighting pinnula is lower.
- The internal bracing of the frame is more central and robust.
- The position of the shades for the index mirror is in the path between the index and horizon mirrors rather than at the top of the instrument.
- Multiple shades are used to allow for different levels of shading.
- Separate shades are provided on the horizon mirror for sighting a low sun position with a very bright horizon.
- The second horizon mirror and accompanying alidade is not provided.

Smith's Astroscope

Caleb Smith, an English insurance broker with a strong interest in astronomy, had created an octant in 1734. He called it an *Astroscope* or *Sea-Quadrant*.[6] His used a fixed prism in addition to an index mirror to provide reflective elements. Prisms provide advantages over mirrors in an era when polished speculum metal mirrors were inferior and both the silvering of a mirror and the production of glass with flat, parallel surfaces was difficult.



Drawing of Smith's Astroscope or Sea-quadrant

In the drawing to the right, the horizon element (B) could be a mirror or a prism. On the index arm, the index mirror (A) rotated with the arm. A sighting telescope was mounted on the frame (C). The index did not use a vernier or other device at the scale (D). Smith called the instrument's index arm a *label*, in the manner of Elton for his mariner's quadrant.[7]

Various design elements of Smith's instrument made it inferior to Hadley's octant and it was not used significantly.[5] For example, one problem with the Astroscope was that angle of the observer's line of sight. By looking down, he had greater difficulty in observing than an orientation with his head in a normal orientation.

Advantages of the octant

The octant provided a number of advantages over previous instruments.

The sight was easy to align because the horizon and the star seem to move together as the ship pitched and rolled. This also created a situation where the error in observation was less dependent on the observer, as he could directly see both objects at once.

With the use of the manufacturing techniques available in the 18th century, the instruments were capable of reading very accurately. The size of the instruments was reduced with no loss of accuracy. An octant could be half the size of a Davis quadrant with no increase in error.

Using shades over the light paths, one could observe the sun directly, while moving the shades out of the light path allowed the navigator to observe faint stars. This made the instrument usable both night and day.

By 1780, the octant and sextant had almost completely eliminated all previous instruments.[5]

Octant reverse side. This side is not seen in photographs very often. On the right, the thumbscrew to adjust the horizon mirror can be seen. At the top, one of the feet on which the octant rests in its case is just below the index arm axis. On the left the notepad is clearly visible. This small keystone-shaped piece of ivory, scarcely larger than a thumbnail, was used by the navigator to record his readings.

Production of the octant

Early octants were constructed primarily in wood, with later versions incorporating ivory and brass components. The earliest mirrors were polished metal, since the technology to produce silvered glass mirrors with flat, parallel surfaces was limited. As glass polishing techniques improved, glass mirrors began to be provided. These used coatings of mercury-containing tin amalgam; coatings of silver or aluminum were not available until the 19th century. The poor optical quality of the early polished speculum metal mirrors meant that telescopic sights were not practical. For that reason, most early octants employed a simple naked-eye sighting pinnula instead.

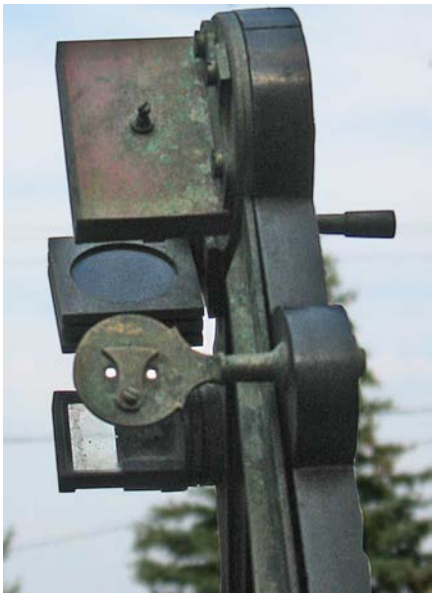
Early octants retained some of the features common to backstaves, such as transversals on the scale. However, as engraved, they showed the instrument to have an apparent accuracy of only two minutes of arc while the backstaff appeared to be accurate to one minute. The use of the vernier scale allowed the scale to be read to one minute, so improved the marketability of the instrument. This and the ease in making verniers compared to transversals, lead to adoption of the vernier on octants produced later in the 18th century.[8]

Details on an octant. This photo shows the graduated scale and the end of the index arm with the vernier. The thumbscrew used to lock the index arm position is seen below the index arm while the thumbscrew used for fine adjustment of the arm is on the left. To the right of the value *50* on the main scale, the SBR logo is engraved. The scale is directly graduated in degrees and thirds of a degree (20'). The vernier can divide the 20' intervals to the nearest minute of arc.

Octants were produced in large numbers. In wood and ivory, their relatively low price compared to an all-brass sextant made them a popular instrument. The design was standardized with many manufacturers using the identical frame style and components. Different shops could make different components, with woodworkers specializing in frames and others in the brass components. For example, Spencer, Browning and Rust, a manufacturer of scientific instruments in England from 1787 to 1840 (operating as *Spencer, Browning and Co.* after 1840) used a Ramsden dividing engine to produce graduated scales in ivory. These were widely used by others and the *SBR* initials could be found on octants from many other manufacturers.[9]

Examples of these very similar octants are in the photos in this article. The image at the top is essentially the same instrument as the one in the detail photos. However, they are from two different instrument makers - the upper is labelled *Crichton - London, Sold by J Berry Aberdeen* while the detail images are of an instrument from *Spencer, Browning & Co. London*. The only obvious difference is the presence of horizon shades on the Crichton octant that are not on the other.

These octants were available with many options. A basic octant with graduations directly on the wood frame were least expensive. These dispensed with a telescopic sight, using a single- or double-holed sighting pinnula instead. Ivory scales would increase the price, as would the use of a brass index arm or a vernier.



Octant details showing the double-holed sighting pinulla. Also visible is the small cover that can block one or the other of the holes. The horizon mirror is on the opposite side of the instrument. The left side is transparent while the tin amalgam on the mirrored side has completely corroded and no longer reflects light. The back of the index mirror's holder is at the top and the three circular glass shades in square frames are between the two mirrors.

Demise of the octant

In 1767 the first edition of the Nautical Almanac tabulated lunar distances, enabling navigators to find the current time from the angle between the sun and the moon. This angle is sometimes larger than 90°, and thus not possible to measure with an octant. For that reason, Admiral John Campbell, who conducted shipboard experiments with the lunar distance method, suggested a larger instrument and the sextant was developed.[10]

From that time onward, the sextant was the instrument that experienced significant development and improvements and was the instrument of choice for naval navigators. The octant continued to be produced well into the 19th century, though it was generally a less accurate and less expensive instrument. The lower price of the octant, including versions without telescope, made it a practical instrument for ships in the merchant and fishing fleets.

One common practice among navigators up to the late nineteenth century was to use both a sextant and an octant. The sextant was used with great care and only for lunars, while the octant was used for routine meridional altitude measurements of the sun every day.[7] This protected the very accurate and pricier sextant, while using the more affordable octant where it performs well.

The bubble octant

From the early 1930s through the end of the 1950s, several types of civilian and military *bubble octant* instruments were produced for use aboard aircraft.[11] All were fitted with an artificial horizon in the form of a bubble, which was centered to align the horizon for a navigator flying thousands of feet above the earth; some had recording features.[12]

Use and adjustment

Use and adjustment of the octant is essentially identical to the navigator's sextant, which see for information on these topics.

Other reflecting instruments

Hadley's was not the first reflecting quadrant. Robert Hooke invented a reflecting quadrant in 1684[13] and had written about the concept as early as 1666.[14] Hooke's was a single-reflecting instrument.[14] Other octants were developed by Jean-Paul Fouchy and Caleb Smith in the early 1730s, however, these did not become significant in the history of navigation instruments.

References

[1] Newton, I., "Newton's Octant" (posthumous description), Philosophical Transactions of the Royal Society, vol. 42, p. 155, 1742

[2] Taylor, E.G.R., *The Haven-finding Art: A History of Navigation from Odysseus to Captain Cook*, Hollis & Carter, London 1971, ISBN 0-370-01347-6

[3] Brewster, Sir David, *Memoirs of the Life, Writings, and Discoveries of Sir Isaac Newton*, Thomas Constable & Co., Edinburgh 1855

[4] Hadley, John, "Hadley's Octant." Philosophical Transactions of the Royal Society, Vol. 37, article 25, p. 147, May 13, 1731.

[5] Daumas, Maurice, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London 1989 ISBN 978-0-7134-0727-3

[6] Bedini, Silvio, *History Corner: Benjamin King of Newport, R.I.-Part II*, Professional Surveyor Magazine, September 1997 Volume 17 Number 6 (http://www.profsurv.com/archive.php?issue=17&article=184)

[7] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1

[8] Bennett, Jim, "Catadioptrics and commerce in eighteenth-century London", in History of Science, vol xliv, 2006, pages 247-277.

[9] Harriet Wynter and Anthony Turner, *Scientific Instruments*, Studio Vista, 1975, ISBN 0-289-70403-0

[10] Gerard L'E. Turner, *Nineteenth Century Scientific Instruments*, Sotheby Publications, 1983, ISBN 0-85667-170-3

[11] Brink, Randall, *Lost Star: The Search for Amelia Earhart*, W. W. Norton & Company, (1994), ISBN 0-393-02683-3, ISBN 978-0-393-02683-2, p. 32

[12] Evolution of the Sextant (http://home.earthlink.net/~nbrass1/cardart.htm)

[13] Chronology of Robert Hooke's life (http://www.roberthooke.org.uk/chronolo.htm)

[14] Charles H. Cotter *The Mariner's Sextant and the Royal Society; Notes and Records of the Royal Society of London*, Vol. 33, No. 1 (Aug., 1978), pp. 23-36.

Backstaff

The **backstaff** is a navigational instrument that was used to measure the altitude of a celestial body, in particular the sun or moon. When observing the sun, users kept the sun to their back (hence the name) and observed the shadow cast by the upper vane on a horizon vane. It was invented by the English navigator John Davis that described it in his book *Seaman's Secrets* in 1594.[]

Davis quadrant from the beginning of the 18th century

Types of backstaffs

Backstaff is the name given to any instrument that measures the altitude of the sun by the projection of a shadow. It appears that the idea for measuring the sun's altitude using back observations originated with Thomas Harriot.[1] Many types of instruments evolved from the cross-staff that can be classified as backstaves. Only the Davis quadrant remains dominant in the history of navigation instruments. Indeed, the Davis quadrant is essentially synonymous with backstaff. However, Davis was neither the first nor the last to design such an instrument and others are considered here as well.

Davis quadrant

Captain John Davis invented a version of the backstaff in 1594. Davis was a navigator who was quite familiar with the instruments of the day such as the mariner's astrolabe, the quadrant and the cross-staff. He recognized the inherent drawbacks of each and endeavoured to create a new instrument that could reduce those problems and increase the ease and accuracy of obtaining solar elevations.

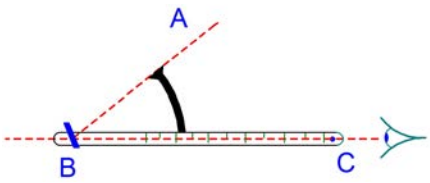


Figure 1 – A simple precursor to the Davis Quadrant after an illustration in his book, *Seaman's Secrets*. The arc was limited to measuring angles to 45°.

One early version of the quadrant staff is shown in *Figure 1*.[2] It had an arc affixed to a staff so that it could slide along the staff (the shape is not critical, though the curved shape was chosen). The arc (A) was placed so that it would cast its shadow on the *horizon vane* (B). The navigator would look along the staff and observe the horizon through a slit in the horizon vane. By sliding the arc so that the shadow aligned with the horizon, the angle of the sun could be read on the graduated staff. This was a simple quadrant, but it was not as accurate as one might like. The accuracy in the instrument is dependent on the length of the staff, but a long staff made the instrument more unwieldy. The maximum altitude that could be measured with this instrument was 45°.

The next version of his quadrant is shown in *Figure 2*.[2] The arc on the top of the instrument in the previous version was replaced with a *shadow vane* placed on a transom. This transom could be moved along a graduated scale to indicate the angle of the shadow above the staff. Below the staff, a 30° arc was added. The horizon, seen through the *horizon vane* on the left, is aligned with the shadow. The *sighting vane* on the arc is moved until it aligns with the view of the horizon. The angle measured is the sum of the angle indicated by the position of the transom and the angle measured on the scale on the arc.

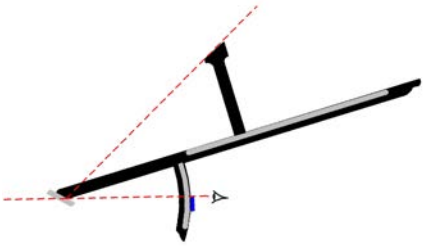


Figure 2 – The second Davis Quadrant after an illustration in his book, *Seaman's Secrets*. The arc above is replaced with an arc below and a shadow-casting transom above. This instrument can now measure up to 90°.

The instrument that is now identified with Davis is shown in *Figure 3*.[3] This form evolved by the mid-17th century.[3] The quadrant arc has been split into two parts. The smaller radius arc, with a span of 60°, was mounted above the staff. The longer radius arc, with a span of 30° was mounted below. Both arcs have a common centre. At the common centre, a slotted *horizon vane* was mounted (B). A moveable *shadow vane* was placed on the upper arc so that its shadow was cast on the horizon vane. A moveable *sight vane* was mounted on the lower arc (C).

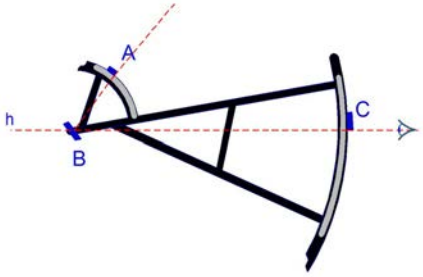


Figure 3 – The Davis Quadrant as it evolved by the mid-17th century. The upper transom has been replaced with a 60° arc.

It is easier for a person to place a vane at a specific location than to read the arc at an arbitrary position. This is due to Vernier acuity, the ability of a person to align two line segments accurately. Thus an arc with a small radius, marked with relatively few graduations, can be used to place the shadow vane accurately at a specific angle. On the other hand, moving the sight vane to the location where the line to the horizon meets the shadow requires a large arc. This is because the position may be at a fraction of a degree and a large arc allows one to read smaller graduations with greater accuracy. The large arc of the instrument, in later years, was marked with transversals to allow the arc to be read to greater accuracy than the main graduations allow.[4]

Thus Davis was able to optimize the construction of the quadrant to have both a small and a large arc, allowing the effective accuracy of a single arc quadrant of large radius without making the entire instrument so large. This form of the instrument became synonymous with the backstaff. It was one of the most widely used forms of the backstaff. Continental European navigators called it the **English Quadrant**.

A later modification of the Davis quadrant was to use a *Flamsteed glass* in place of the shadow vane; this was suggested by John Flamsteed.[3] This placed a lens on the vane that projected an image of the sun on the horizon vane instead of a shadow. It was useful under conditions where the sky was hazy or lightly overcast; the dim image of the sun was shown more brightly on the horizon vane where a shadow could not be seen.[4]

Usage

In order to use the instrument, the navigator would place the shadow vane at a location anticipating the altitude of the sun. Holding the instrument in front of him, with the sun at his back, he holds the instrument so that the shadow cast by the shadow vane falls on the horizon vane at the side of the slit. He then moves the sight vane so that he observes the horizon in a line from the sight vane through the horizon vane's slit while simultaneously maintaining the position of the shadow. This permits him to measure the angle between the horizon and the sun as the sum of the angle read from the two arcs.

Since the shadow's edge represents the limb of the sun, he must correct the value for the semidiameter of the sun.

Instruments that derived from the Davis quadrant

The Elton's quadrant derived from the Davis quadrant. It added an index arm with spirit levels to provide an artificial horizon.

Demi-cross

The **demi-cross** was an instrument that was contemporary with the Davis quadrant. It was popular outside of England.[3]

The vertical transom was like a half-transom on a cross-staff, hence the name *demi-cross*. It supported a *shadow vane* (A in *Figure 4*) that could be set to one of several heights (three according to May,[3] four according to de Hilster[5]). By setting the shadow vane height, the range of angles that could be measured was set. The transom could be slid along the staff and the angle read from one of the graduated scales on the staff.

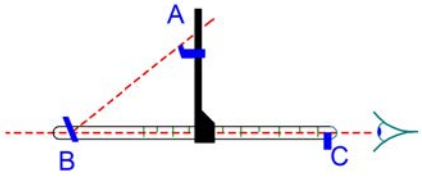


Figure 4 – A demi-cross. This instrument was contemporary with the Davis quadrant and popular outside England. It shows its similarity with the first of Davis' versions (*Figure 1*)

The *sight vane* (C) and *horizon vane* (B) were aligned visually with the horizon. With the shadow vane's shadow cast on the horizon vane and aligned with the horizon, the angle was determined. In practice, the instrument was accurate but more unwieldy than the Davis quadrant.[5]

The plough

The **plough** was the name given to an unusual instrument that existed for a short time.[3] It was part cross-staff and part backstaff. In *Figure 5*, *A* is the transom that casts its shadow on the horizon vane at *B*. It functions in the same manner as the staff in *Figure 1*. *C* is the sighting vane. The navigator uses the sighting vane and the horizon vane to align the instrument horizontally. The sighting vane can be moved left to right along the staff. *D* is a transom just as one finds on a cross-staff. This transom has two vanes on it that can be moved closer or farther from the staff to emulate different-length transoms. The transom can be moved on the staff and used to measure angles.

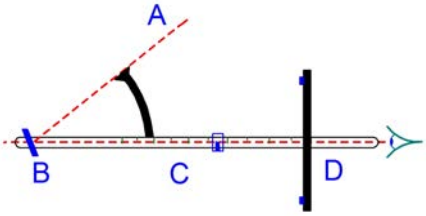


Figure 5 – The plough – a transitional instrument with the characteristics of both a cross-staff and a backstaff.

Almucantar staff

The **Almucantar staff** is a device specifically used for measuring the altitude of the sun at low altitudes.

Cross-staff

The **cross-staff** was normally a direct observation instrument. However, in later years it was modified for use with back observations.

Quadrant

There was a variation of the quadrant – the Back observation quadrant – that was used for measuring the sun's altitude by observing the shadow cast on a horizon vane.

Thomas Hood cross-staff

Thomas Hood invented this cross-staff in 1590.[3] It could be used for surveying, astronomy or other geometric problems.

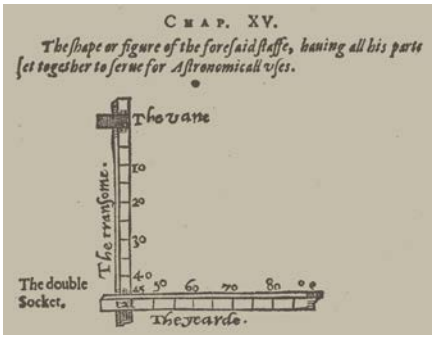


Figure 6 – Cross-staff by Thomas Hood. Though called a cross-staff, this instrument uses a shadow vane to cast a shadow on the instrument to measure the altitude of the sun.

It consists of two components, a transom and a yard. The transom is the vertical component and is graduated from 0° at the top to 45° at the bottom. At the top of the transom, a vane is mounted to cast a shadow. The yard is horizontal and is graduated from 45° to 90°. The transom and yard are joined by a special fitting (the *double socket* in *Figure 6*) that permits independent adjustments of the transom vertically and the yard horizontally.

It was possible to construct the instrument with the yard at the top of the transom rather than at the bottom.[6]

Initially, the transom and yard are set so that the two are joined at their respective 45° settings. The instrument is held so that the yard is horizontal (the navigator can view the horizon along the yard to assist in this). The socket is loosened so that the transom is moved vertically until the shadow of the vane is cast at the yard's 90° setting. If the movement of just the transom can accomplish this, the altitude is given by the transom's graduations. If the sun is too high for this, the yard horizontal opening in the socket is loosened and the yard is moved to allow the shadow to land on the 90° mark. The yard then yields the altitude.

It was a fairly accurate instrument, as the graduations were well spaced compared to a conventional cross-staff. However, it was a bit unwieldy and difficult to handle in wind.

Benjamin Cole quadrant

A late addition to the collection of backstaves in the navigation world, this device was invented by Benjamin Cole in 1748.[3]

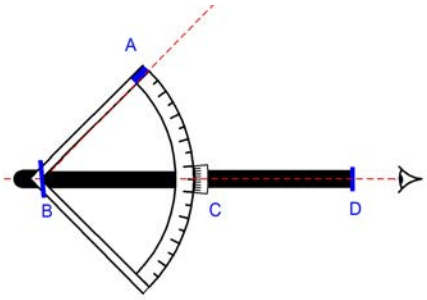


Figure 7 – Cole quadrant from 1748.

The instrument consists of a staff with a pivoting quadrant on one end. The quadrant has a *shadow vane*, which can optionally take a lens like the Davis quadrant's Flamsteed glass, at the upper end of the graduated scale (A in *Figure 7*). This casts a shadow or projects an image of the sun on the *horizon vane* (B). The observer views the horizon through a hole in the *sight vane* (D) and a slit in the horizon vane to ensure the instrument is level. The quadrant component is rotated until the horizon and the sun's image or shadow are aligned. The altitude can then be read from the quadrant's scale. In order to refine the reading, a circular vernier is mounted on the staff (D).

The fact that such an instrument was introduced in the middle of the 18th century shows that the quadrant was still a viable instrument even in the presence of the octant.

George Adams Sr. created a very similar backstaff at the same time. Adam's version ensured that the distance between the Flamsteed glass and horizon vane was the same as the distance from the vane to the sight vane.[7]

Cross bow quadrant

Edmund Gunter invented the **cross bow quadrant**, also called the **mariner's bow**, around 1623.[3] It gets its name from the similarity to the archer's crossbow.

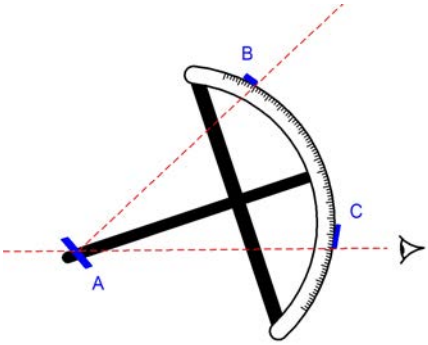


Figure 8 – Drawing of a cross bow quadrant. The 120° arc was graduated with as a 90° arc, resulting in divisions that are slightly greater than their nominal arc size.

This instrument is interesting in that the arc is 120° but is only graduated as a 90° arc.[3] As such, the angular spacing of a degree on the arc is slightly greater than one degree. Examples of the instrument can be found with a 0° to 90° graduation or with two mirrored 0° to 45° segments centred on the midpoint of the arc.[3]

The instrument has three vanes, a *horizon vane* (A in *Figure 8*) which has an opening in it to observe the horizon, a *shadow vane* (B) to cast a shadow on the horizon vane and a *sighting vane* (C) that the navigator uses to view the horizon and shadow at the horizon vane. This serves to ensure the instrument is level while simultaneously measuring the altitude of the sun. The altitude is the difference in the angular positions of the shadow and sighting vanes.

With some versions of this instrument, the sun's declination for each day of the year was marked on the arc. This permitted the navigator to set the shadow vane to the date and the instrument would read the altitude directly.

References

- Ephraim Chambers, Cyclopædia, The First Volume, 1728 [8] explaining the use of a backstaff
- Maurice Daumas, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London 1989 ISBN 978-0-7134-0727-3
- Gerard L'Estrange Turner, *Antique Scientific Instruments*, Blandford Press Ltd. 1980 ISBN 0-7137-1068-3

Notes

[2] The Seaman's Secrets (http://www.mcallen.lib.tx.us/books/seasecr/dseasec0.htm); text of Davis' publication with illustrations.

[3] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1

[4] Bennett, Jim, "Catadioptrics and commerce in eighteenth-century London", in History of Science, vol xliv, 2006, pages 247–277.

[5] Nicolàs de Hilster's web site (http://www.dehilster.info/index.php?doc=http://www.dehilster.info/instrumenten/demi-cross/index.html) Web page documenting an excellent reproduction of a demi-cross.

[7] Charles Hutton, *A Mathematical and Philosophical Dictionary* (http://archimedes.mpiwg-berlin.mpg.de/cgi-bin/archim/dict/hw?lemma=QUADRANT&step=entry&id=d006)

[8] http://digicoll.library.wisc.edu/cgi-bin/HistSciTech/HistSciTech-idx?type=turn&entity=HistSciTech000900240225&isize=L

External links

- "Backstaff" at answers.com (http://www.answers.com/topic/backstaff?cat=technology) – Good diagram of how a backstaff is held in use.

Attribution

This article incorporates text from a publication now in the public domain: Chambers, Ephraim, ed. (1728). "article name needed". *Cyclopaedia, or an Universal Dictionary of Arts and Sciences* (first ed.). James and John Knapton, *et al.*

Mariner's astrolabe

The **mariner's astrolabe**, also called **sea astrolabe**, was an inclinometer used to determine the latitude of a ship at sea by measuring the sun's noon altitude (declination) or the meridian altitude of a star of known declination. Not an astrolabe proper, the mariner's astrolabe was rather a graduated circle with an alidade used to measure vertical angles. They were designed to allow for their use on boats in rough water and/or in heavy winds, which astrolabes are ill equipped to handle. In the sixteenth century, the instrument was also called a **ring**.[1]

Three Mariner's Astrolabes in the Museum of the Forte da Ponta da Bandeira; Lagos, Portugal

History

Many dates can be found for the appearance of the first mariner's astrolabes. The earliest date, 1295, is offered by the Majorcan astronomer Ramon Llull.[2] Later dates centre around the late 15th century, with Samuel Purchas claiming that it was adapted for marine navigation by Martin Behaim,[2] a mariner not considered a trustworthy source by some historians. In any event, the instrument was certainly known by the end of the 15th century. Nevertheless, the creation and perfectioning of the mariner's astrolabe is attributed to Portuguese navigators during the beginning of Portuguese discoveries.[3][4] The earliest known description of how to make and use a sea astrolabe comes from Martín Cortés de Albacar's[5] *Arte de Navegar* published in 1551,[6] although the basic principle is the same as that of the archipendulum used in constructing the Egyptian pyramids.

There is strong evidence that the mariner's astrolabe was derived directly from the planispheric astrolabe, as the earliest examples retain some of the markings (e.g. *umbra recta* and *umbra versa*) of the prior device without having the same components.[7]

Mariner's astrolabe in Maritime Museum, Lisbon

The mariner's astrolabe would have replaced or complemented instruments such as the cross staff or quadrant as a navigator's instrument. The mariner's astrolabe was used until the middle or, at the latest, the end of the 17th century.[7] It was replaced by more accurate and easier-to-use instruments such as the Davis quadrant.

Although their heavy brass construction permits their longevity in marine environments,[6] mariner's astrolabes are very rare today. In 1979, only 35 were known to exist.[8] while 65 were known by 1988.[9] The biggest collection remains in museums in Portugal.[4]

Aveiro (1575) - Maritime Museum, Lisbon

Construction

Mariner's astrolabes were made of brass. Since weight was advantageous when using the instrument on the heaving deck of a ship or in high winds, other materials, such as wood or ivory, were not desirable though some wood sea astrolabes were made. Early sea astrolabes were made from sheets of brass. Due to their light weight, they tended to perform poorly at sea. Heavier cast brass frames began to be made in the mid-sixteenth century and were considerably better.[1] As the accuracy of the instrument is related to the radius of the divided circle, these were made as large as practical.

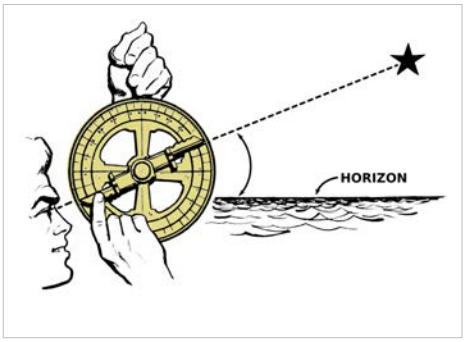
Since the large plate form of the planispheric astrolabe makes it sensitive to the wind, the mariner's astrolabe is made with a frame form. The openings in the frame allow wind to pass through, inducing less motion in the instrument.

The essential function of the device was to measure angles. Thus the instrument featured a ring graduated in degrees. Early instruments were only graduated for 90°; later instruments were graduated for the full 360° circle around the limb. The sole purpose of the spokes was to support the pivot point for the alidade. In order to lower the centre of gravity of the device and thus increase its period of motion as a means of stabilizing it, extra brass was usually added to the bottom of the instrument inside the ring. This is clearly evident in the lower left instrument seen in the photograph above.

The alidade was free to rotate about a pin through the centre of the instrument. The vanes of the alidade were either slotted or pierced with a hole to allow the user to align the alidade.

The astrolabe had a ring attached to the top of the instrument to allow it to hang vertically.

Usage



In order to use the astrolabe, the navigator would hold the instrument by the ring at the top. This caused the instrument to remain in a vertical plane. He would align the plane of the astrolabe to the direction of the object of interest. The alidade was aligned to point at the object and the altitude was read off the outer degree scale.

If observing a dim object such as a star, the navigator would observe the object directly through the alidade. If observing the sun, it was both safer and easier to allow the shadow of one of the alidade's vanes to be cast onto the opposite vane.

Limitations

The mariner's astrolabe needed to be suspended vertically in order to measure the altitude of the celestial object. This meant it could not be used easily on the deck in windy conditions. It could not easily be used to measure the angle between two objects, which was necessary for longitude calculations by the lunar distance method (though that technique was not used when the instrument was developed). Another limitation was that the instrument's angular accuracy was directly proportional to the length of the alidade, which was not very long.

References

[1] Waters, David Watkin, *The Art of Navigation in England in Elizabethan and Early Stuart Times*, Yale University Press, 1958

[2] *The Oxford Companion to Ships and the Sea*, Peter Kemp ed., 1976 ISBN 0-586-08308-1

[4] http://www.ancruzeiros.pt/anci-astrolabio.html

[5] See es:Martín Cortés de Albacar for the Spanish Wikipedia biography

[6] Swanick, Lois Ann. *An Analysis Of Navigational Instruments In The Age Of Exploration: 15th Century To Mid-17th century*, MA Thesis, Texas A&M University, December 2005

[7] Daumas, Maurice, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London 1989 ISBN 978-0-7134-0727-3

[8] Turner, Gerard L'E. *Antique Scientific Instruments*, Blandford Press Ltd. 1980 ISBN 0-7137-1068-3

[9] A. Stimson, *The Mariner's Astrolabe. A survey of known, surviving sea astrolabes.* Hes & De Graff Pub B V (March 1988) ISBN 978-90-6194-017-3

External links

- Make your own mariner's astrolabe (http://www.astrolabes.org/mariner.htm)
- Champlain's astrolabe at the Canadian Museum of Civilization (http://www.civilization.ca/tresors/treasure/222eng.html) Believed to be Samuel de Champlain's lost astrolabe.

Astrolabe

An **astrolabe** (Greek: ἀστρολάβος *astrolabos*, "star-taker")[1] is an elaborate inclinometer, historically used by astronomers, navigators, and astrologers. Its many uses include locating and predicting the positions of the Sun, Moon, planets, and stars, determining local time given local latitude and vice-versa, surveying, triangulation, and to cast horoscopes. It was used in classical antiquity, the Islamic Golden Age, the European Middle Ages and Renaissance for all these purposes. In the Islamic world, it was also used to calculate the Qibla and to find the times for Salah, prayers.

Astrolabe quadrant, England, 1388

There is often confusion between the astrolabe and the mariner's astrolabe. While the astrolabe could be useful for determining latitude on land, it was an awkward instrument for use on the heaving deck of a ship or in wind. The mariner's astrolabe was developed to address these issues.

Etymology

A 16th-century astrolabe, showing a *tulip* rete and rule

OED gives the translation "star-taker" for the English word "astrolabe" and traces it, through medieval Latin, to the Greek word *astrolabos*[1][2] from astron "star" and lambanein "to take".[3] In the medieval Islamic world the word "asturlab" (i.e. astrolabe) was given various etymologies. In Arabic texts the word is translated as "akhdh al-kawakib" (lit. "taking the stars") which corresponds to an interpretation of the Greek word.[] Al-Biruni quotes and criticizes the medieval scientist Hamza al-Isfahani who had stated:[] "asturlab is an arabization of this Persian phrase" (*sitara yab*, meaning "taker of the stars").[4] In medieval Islamic sources there is also a "fictional" and popular etymology of the words as "lines of lab". In this popular etymology "Lab" is a certain son of Idris (=Enoch). This etymology is mentioned by a 10th-century scientist called al-Qummi but rejected by al-Khwarizmi.[5] "Lab" in Arabic also means "sun" and "black stony places" (cf. Dictionary).

History

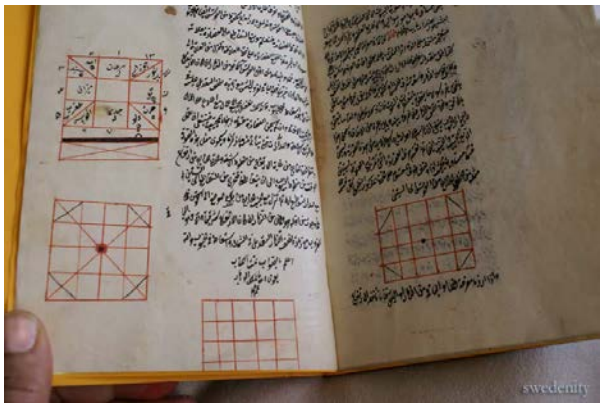
Ancient world

An early astrolabe was invented in the Hellenistic world in 150 BC and is often attributed to Hipparchus. A marriage of the planisphere and dioptra, the astrolabe was effectively an analog calculator capable of working out several different kinds of problems in spherical astronomy. Theon of Alexandria wrote a detailed treatise on the astrolabe, and Lewis (2001) argues that Ptolemy used an astrolabe to make the astronomical observations recorded in the *Tetrabiblos*.[6]

Astrolabes continued in use in the Greek-speaking world throughout the Byzantine period. About 550 AD the Christian philosopher John Philoponus wrote a treatise on the astrolabe in Greek, which is the earliest extant Greek treatise on the instrument.[7] In addition, Severus Sebokht, a bishop who lived in Mesopotamia, also wrote a treatise on the astrolabe in Syriac in the mid-7th century.[8] Severus Sebokht refers in the introduction of his treatise to the astrolabe as being made of brass, indicating that metal astrolabes were known in the Christian East well before they were developed in the Islamic world or the Latin West.[9]

Medieval era

Astrolabes were further developed in the medieval Islamic world, where Muslim astronomers introduced angular scales to the astrolabe,[10] adding circles indicating azimuths on the horizon.[11] It was widely used throughout the Muslim world, chiefly as an aid to navigation and as a way of finding the Qibla, the direction of Mecca. The first person credited with building the astrolabe in the Islamic world is reportedly the 8th century mathematician Muhammad al-Fazari.[12] The mathematical background was established by the Muslim astronomer Albatenius in his treatise *Kitab az-Zij* (ca. 920 AD), which was translated into Latin by Plato Tiburtinus (*De Motu Stellarum*). The earliest surviving dated astrolabe [13] is dated AH 315 (927/8 AD). In the Islamic world, astrolabes were used to find the times of sunrise and the rising of fixed stars, to help schedule morning prayers (salat). In the 10th century, al-Sufi first described over 1,000 different uses of an astrolabe, in areas as diverse as astronomy, astrology, horoscopes, navigation, surveying, timekeeping, prayer, Salah, Qibla, etc.[14][15]



A Treatise explaining the importance of the Astrolabe by Nasir al-Din al-Tusi, Persian scientist.

Astrolabe of Jean Fusoris, made in Paris, 1400

An 18th-century Persian astrolabe

Disassembled 18th-century astrolabe

The spherical astrolabe, a variation of both the astrolabe and the armillary sphere, was invented during the Middle Ages by astronomers and inventors in the Islamic world.[16] The earliest description of the spherical astrolabe dates back to Al-Nayrizi (fl. 892–902). In the 12th century, Sharaf al-Dīn al-Tūsī invented the *linear astrolabe*, sometimes called the "staff of al-Tusi," which was "a simple wooden rod with graduated markings but without sights. It was furnished with a plumb line and a double chord for making angular measurements and bore a perforated pointer."[] The first geared mechanical astrolabe was later invented by Abi Bakr of Isfahan in 1235.[17]

Astrolabium Masha'Allah Public Library Brugge Ms. 522

Peter of Maricourt, in the last half of the 13th century, also wrote a treatise on the construction and use of a universal astrolabe (*Nova compositio astrolabii particularis*). Universal astrolabes can be found at the History of Science Museum in Oxford.

The English author Geoffrey Chaucer (ca. 1343–1400) compiled a treatise on the astrolabe for his son, mainly based on Messahalla. The same source was translated by the French astronomer and astrologer Pelerin de Prusse and others. The first printed book on the astrolabe was *Composition and Use of Astrolabe* by Cristannus de Prachaticz, also using Messahalla, but relatively original.

In 1370, the first Indian treatise on the astrolabe was written by the Jain astronomer Mahendra Suri.[18]

The first known metal astrolabe in Western Europe is the Destombes astrolabe made from brass in tenth-century Spain.,.[19][20] Metal astrolabes improved on the accuracy of their wooden precursors. The astrolabe was almost certainly first brought north of the Pyrenees by Gerbert of Aurillac (future Pope Sylvester II), where it was integrated into the quadrivium at the school in Reims, France, sometime before the turn of the 11th century.[21] In the 15th century, the French instrument-maker Jean Fusoris (ca. 1365–1436) also started selling astrolabes in his shop in Paris, along with portable sundials and other popular scientific gadgets of the day. Thirteen of his astrolabes survive to this day.[22] Finally, one more special example of craftsmanship in the early 15th-century Europe is the astrolabe dated 1420, designed by Antonius de Pacento and made by Dominicus de Lanzano.[23]

In the 16th century, Johannes Stöffler published *Elucidatio fabricae ususque astrolabii*, a manual of the construction and use of the astrolabe. Four identical 16th-century astrolabes made by Georg Hartmann provide some of the earliest evidence for batch production by division of labor.

Astrolabes and clocks

At first mechanical astronomical clocks were influenced by the astrolabe; in many ways they could be seen as clockwork astrolabes designed to produce a continual display of the current position of the sun, stars, and planets. For example, Richard of Wallingford's clock (c. 1330) consisted essentially of a star map rotating behind a fixed rete, similar to that of an astrolabe.[24]

Many astronomical clocks, such as the famous clock at Prague, use an astrolabe-style display, adopting a stereographic projection (see below) of the ecliptic plane.

In recent times, astrolabe watches have become a feature of haute horologie. For example, in 1985 Swiss watchmaker Dr. Ludwig Oechslin designed and built an astrolabe wristwatch [25] in conjunction with Ulysse Nardin. Dutch watchmaker Christaan van der Klauuw [26] also manufactures astrolabe watches today.

A modern Persian astrolabe, made in Tabriz in 2013.

Construction

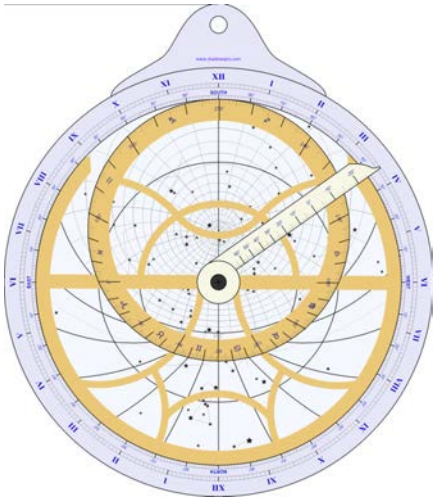
An astrolabe consists of a disk, called the *mater* (mother), which is deep enough to hold one or more flat plates called *tympans*, or *climates*. A tympan is made for a specific latitude and is engraved with a stereographic projection of circles denoting azimuth and altitude and representing the portion of the celestial sphere above the local horizon. The rim of the mater is typically graduated into hours of time, degrees of arc, or both. Above the mater and tympan, the *rete*, a framework bearing a projection of the ecliptic plane and several pointers indicating the positions of the brightest stars, is free to rotate. These pointers are often just simple points, but depending on the skill of the craftsman can be very elaborate and artistic. There are examples of astrolabes with artistic pointers in the shape of balls, stars, snakes, hands, dogs' heads, and leaves, among others.[27] Some astrolabes have a narrow *rule* or *label* which rotates over the rete, and may be marked with a scale of declinations.

The Hartmann astrolabe in Yale's collection. This instrument shows its rete and rule.

The rete, representing the sky, functions as a star chart. When it is rotated, the stars and the ecliptic move over the projection of the coordinates on the tympan. One complete rotation corresponds to the passage of a day. The astrolabe is therefore a predecessor of the modern planisphere.

On the back of the mater there is often engraved a number of scales that are useful in the astrolabe's various applications; these vary from designer to designer, but might include curves for time conversions, a calendar for converting the day of the month to the sun's position on the ecliptic, trigonometric scales, and a graduation of 360 degrees around the back edge. The *alidade* is attached to the back face. An alidade can be seen in the lower right illustration of the Persian astrolabe above. When the astrolabe is held vertically, the alidade can be rotated and the sun or a star sighted along its length, so that its altitude in degrees can be read ("taken") from the graduated edge of the astrolabe; hence the word's Greek roots: "astron" (ἄστρον) = star + "lab-" (λαβ-) = to take.

Celestial Globe, Isfahan (?), Iran 1144. Shown at the Louvre Museum, this globe is the 3rd oldest surviving in the world



Computer-generated planispheric astrolabe

Notes

[1] astrolabe (http://dictionary.oed.com/cgi/entry/50013806), *Oxford English Dictionary* 2nd ed. 1989

[2] Astrolabe (http://oxforddictionaries.com/definition/english/astrolabe?q=astrolabe), on Oxford Dictionaries

[3] http://www.etymonline.com/index.php?term=astrolabe

[6] "The astrolabe was in fact an invention of the ancient Greeks."
"It is generally accepted that Greek astrologers, in either the first or second centuries BC, invented the *astrolabe*, an instrument that measures the altitude of stars and planets above the horizon. Some historians attribute its invention to Hipparchus"

[7] Modern editions of John Philoponus' treatise on the astrolabe are *On the Use and Construction of the Astrolabe,* ed. H. Hase, Bonn: E. Weber, 1839 (or id. Rheinisches Museum für Philologie 6 (1839): 127–71); repr. and translated into French by A.P. Segonds, *Jean Philopon, traité de l'astrolabe,* Paris: Librairie Alain Brieux, 1981; and translated into English by H.W. Green in R.T. Gunther, *The Astrolabes of the World,* Vol. 1/2, Oxford, 1932, repr. London: Holland Press, 1976, pp. 61–81.

[8] "The most distinguished Syriac scholar of this later period was Severus Sebokht (d. 666-7), Bishop of Kennesrin. [...] In addition to these works [...] he also wrote on astronomical subjects (Brit. Mus. Add. 14538), and composed a treatise on the astronomical instrument known as the astrolabe, which has been edited and published by F. Nau (Paris, 1899)."
Severus' treatise was translated by Jessie Payne Smith Margoliouth in R.T. Gunther, *Astrolabes of the World*, Oxford, 1932, pp. 82–103.

[9] Severus Sebokht, *Description of the astrolabe* http://www.tertullian.org/fathers/severus_sebokht_astrolabe_01_trans.htm

[10] See p. 289 of

[12] Richard Nelson Frye: *Golden Age of Persia*. p. 163

[13] http://www.soas.ac.uk/gallery/islamicpatronage/popup25732.html

[14] Dr. Emily Winterburn (National Maritime Museum), Using an Astrolabe (http://www.muslimheritage.com/topics/default.cfm?ArticleID=529), Foundation for Science Technology and Civilisation, 2005.

[16] Emilie Savage-Smith (1993). "Book Reviews", *Journal of Islamic Studies* **4** (2), pp. 296–299.

[17] Silvio A. Bedini, Francis R. Maddison (1966). "Mechanical Universe: The Astrarium of Giovanni de' Dondi", *Transactions of the American Philosophical Society* **56** (5), pp. 1–69.

[19] "Qantara, Mediterranean Heritage"http://www.qantara-med.org/qantara4/public/show_document.php?do_id=1379&lang=en

[20] Nancy Marie Brown (2010), "The Abacus and the Cross". Page 140. Basic Books. ISBN 978-0-465-00950-3

[21] Nancy Marie Brown (2010), "The Abacus and the Cross". Page 143. basic Books. ISBN 978-0-465-00950-3

[23] Ralf Kern (2010), *Wissenschaftliche Instrumente in ihrer Zeit*. Band 1: Vom Astrolab zum mathematischen Besteck. Cologne, S. 204. ISBN 978-3-86560-865-9

[24] North (2005)

[25] http://www.ulysse-nardin.ch/en/swiss_watch_manufacturer/Collection/Archive/Astrolabium_G._Galilei.html

[26] http://www.klaauw.com/

References

- Evans, James (1998), *The History and Practice of Ancient Astronomy*, Oxford University Press, ISBN 0-19-509539-1.
- Alessandro Gunella and John Lamprey, *Stoeffler's Elucidatio* (translation of Elucidatio fabricae ususque astrolabii into English). Published by John Lamprey, 2007.
- Krebs, Robert E.; Krebs, Carolyn A. (2003), *Groundbreaking Scientific Experiments, Inventions, and Discoveries of the Ancient World*, Greenwood Press.
- Edgar Laird. "Astrolabes and the Construction of Time in the Late Middle Ages." In: *Constructions of Time in the Late Middle Ages*. Ed. Carol Poster and Richard Utz. Evanston, IL: Northwestern University Press, 1997, pp. 51–69.
- King, D. A (1981), "The Origin of the Astrolabe According to the Medieval Islamic Sources", *Journal for the History of Arabic Science* **5**: 43–83
- Lewis, M. J. T. (2001), *Surveying Instruments of Greece and Rome*, Cambridge University Press.
- Morrison, James E (2007), *The Astrolabe*, Janus, ISBN 978-0-939320-30-1.
- John David North (2005), *God's Clockmaker: Richard of Wallingford and the Invention of Time*, Continuum International Publishing Group, ISBN 978-1-85285-451-5
- Critical edition of *Pelerin de Prusse on the Astrolabe* (translation of *Practique de Astralabe*). Editors Edgar Laird, Robert Fischer. Binghamton, New York, 1995, in *Medieval & Renaissance Texts & Studies*. ISBN 0-86698-132-2
- King, Henry *Geared to the Stars: the Evolution of Planetariums, Orreries, and Astronomical Clocks* University of Toronto Press, 1978

External links

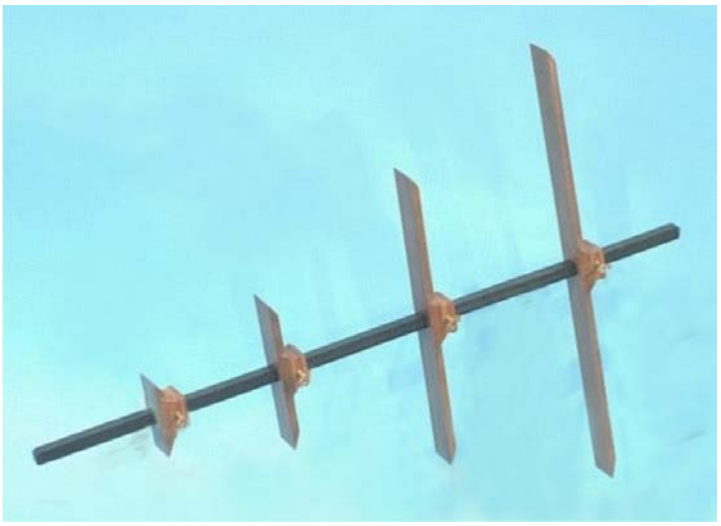
- paper astrolabe generator, from the ESO (http://www.eso.org/~ohainaut/bin/astrolabe.cgi)
- "Hello World!" for the Astrolabe: The First Computer (http://blip.tv/file/2260323) Video of Howard Covitz's Presentation at Ignite Phoenix, June 2009. Slides for Presentation (http://www.slideshare.net/hcovitz/the-astrolabe-the-first-computer-or-hello-world-on-the-astrolabe) Licensed as Creative Commons by-nc-nd.
- Video of Tom Wujec demonstrating an astrolabe. (http://www.ted.com/talks/tom_wujec_demos_the_13th_century_astrolabe.html) Taken at TEDGlobal 2009. Includes clickable transcript. Licensed as Creative Commons by-nc-nd.
- The Astrolabe (http://www.astrolabes.org)
- A working model of the Dr. Ludwig Oechslin's Astrolabium Galileo Galilei watch (http://www.rogivue.com/xoops/modules/news/article.php?storyid=13)
- Ulysse Nardin Astrolabium Galilei Galileo: A Detailed Explanation (http://www.rogivue.com/xoops/modules/news/article.php?storyid=14)
- Fully illustrated online catalogue of world's largest collection of astrolabes (http://www.mhs.ox.ac.uk/astrolabe/)
- Gerbert d'Aurillac's use of the Astrolabe (http://mathdl.maa.org/convergence/1/?pa=content&sa=viewDocument&nodeId=1187&bodyId=1326) at Convergence (http://mathdl.maa.org/convergence/1/)
- Mobile astrolabe and horologium (http://www.myastrolabe.org)
- medieval equal hour horary quadrant (http://www.abc.net.au/news/2011-11-09/one-man27s-trash-is-another27s-centuries-old-treasure/3654974)

Jacob's staff

For the plant known as the ocotillo, sometimes called the Jacob's staff, see ocotillo.

The term **Jacob's staff**, also **cross-staff**, a **ballastella**, a **fore-staff**, or a **balestilha**, is used to refer to several things. This can lead to considerable confusion unless one clarifies the purpose for the object so named. The two most frequent uses are:

- in astronomy and navigation for a simple device to measure angles, later replaced by the more precise sextants;
- in surveying for a vertical rod that penetrates the ground and supports a compass or other instrument.



Jacob's staff with four transoms

Astronomy and navigation

In navigation the instrument is also called a **cross-staff** and was used to determine angles, for instance the angle between the horizon and Polaris or the sun to determine a vessel's latitude, or the angle between the top and bottom of an object to determine the distance to said object if its height is known, or the height of the object if its distance is known, or the horizontal angle between two visible locations to determine one's point on a map.

The Jacob's staff, when used for astronomical observations, was also referred to as a **radius astronomicus**. With the demise of the cross-staff, in the modern era the name "Jacob's staff" is applied primarily to the device used to provide support for surveyor's instruments.

History

The origin of the name of the instrument is not certain. Some refer to the Biblical patriarch Jacob,[1] specifically Gen 32:11 [2].[1] It may also take its name after its resemblance to Orion, referred to by the name of Jacob on some medieval star charts.[3][4] Another possible source is the Pilgrim's staff, the symbol of St James (Jacobus in Latin). The name *cross staff* simply comes from its cruciform shape.

The original Jacob's staff was developed as a single pole device in the 14th century that was used in making astronomical measurements. It was first described by the Jewish mathematician Levi ben Gerson[5][6] of Provence. However, its invention was likely due to Jacob ben Makir who also lived in Provence in the same period.[7] Attributions to 15th century astronomer Georg Purbach[8] are less likely correct, since Purbach was not born until 1423. Such attributions may refer to a different instrument with the same name. May[9] states that its origins can be traced to the Chaldeans around 400 BC.

Although it has become quite accepted that Levi ben Gerson first described Jacob's staff, the Sinologist Joseph Needham theorizes that the Song Dynasty Chinese scientist Shen Kuo (1031–1095), in his *Dream Pool Essays* of 1088, described a Jacob's staff.[10] Shen was an antiquarian interested in ancient objects; after he unearthed an ancient crossbow-like device from a home's garden in Jiangsu, he realized it had a sight with a graduated scale that could be used to measure the heights of distant mountains, likening it to how mathematicians measure heights by using right-angle triangles.[10] He wrote that when one viewed the whole breadth of a mountain with it, the distance

on the instrument was long; when viewing a small part of the mountainside, the distance was short; this, he wrote, was due to the cross piece that had to be pushed further away from the eye, while the graduation started from the further end. Needham does not mention any practical application of this observation.[10]

During the Renaissance, the Dutch mathematician and surveyor Metius is known to have developed his own Jacob's staff. Gemma Frisius is also known to have made improvements to this instrument. Johannes Müller, called Regiomontanus, made the Jacob's staff in the 15th century to a popular instrument in geodesic and astronomical measurements.[11]

Construction

In the original form of the cross-staff, the pole or main staff was marked with graduations for length. The cross-piece (*BC* in the drawing to the right), also called the *transom* or *transversal*, slides up and down on the main staff. On older instruments, the ends of the transom were cut straight across. Newer instruments had brass fittings on the ends with holes in the brass for observation. In marine archaeology, these fittings are often the only components of a cross-staff that survive.[12]

It was common to provide several transoms, each with a different range of angles it would measure. Three transoms were common. In later instruments, separate transoms were switched in favour of a single transom with pegs to indicate the ends. These pegs mounted in one of several pairs of holes symmetrically located on either side of the transom. This provided the same capability with fewer parts.[9] The transom on Frisius' version had a sliding vane on the transom as an end point.[9]

A Jacob's staff, from John Sellers' *Practical Navigation* (1672)

Usage

The navigator places one end of the main staff against his cheek just below his eye. He sights the horizon at the end of the lower part of the transom (or through the hole in the brass fitting) (*B*), adjusting the cross arm on the main arm until he or she can sight the sun at the other end of the transom (*C*). The altitude can then be determined by reading the position of the transom on the scale on the main staff. This value was converted to an angular measurement by looking up the value in a table.

Cross-staff for navigation

The original version was not used at sea. Johannes Werner suggested the cross-staff be used at sea in 1514[9] and improved instruments were introduced for use in navigation. John Dee introduced it to England in the 1550s.[1] In the improved versions, the rod was graduated directly in degrees. This variant of the instrument is not correctly termed a *Jacob's staff* but is a cross-staff.[7]

The cross-staff was difficult to use. In order to get consistent results, the observer had to position the end of the pole precisely against his cheek. He had to observe the horizon and a star in two different directions while not moving the instrument when he shifted his gaze from one to the other. In addition, observations of the sun required the navigator to look directly at the sun. This could be a painful exercise and made it difficult to obtain an accurate altitude for the sun. Mariners took to mounting smoked-glass to the ends of the transoms to reduce the glare of the sun.[9][13]

As a navigational tool, this instrument was eventually replaced, first by the backstaff or quadrant, neither of which required the user to stare directly into the sun, and later by the octant and the sextant. Perhaps influenced by the backstaff, some navigators modified the cross-staff to operate more like the former. Vanes were added to the ends of the longest cross-piece and another to the end of the main staff. The instrument was reversed so that the shadow of the upper vane on the cross piece fell on the vane at the end of the staff. The navigator held the instrument so that he would view the horizon lined up with the lower vane and the vane at the end of the staff. By aligning the horizon with the shadow of the sun on the vane at the end of the staff, the elevation of the sun could be determined.[14] This actually increased the accuracy of the instrument, as the navigator no longer had to position the end of the staff precisely on his cheek.

Another variant of the cross-staff was a spiegelboog, invented in 1660 by the Dutchman, Joost van Breen.

Ultimately, the cross-staff could not compete with the backstaff in many countries. In terms of handling, the backstaff was found to be more easy to use.[15] However, it has been proven by several authors that in terms of accuracy, the cross-staff was superior to the backstaff.[16] Backstaves were no longer allowed on board Dutch East India Company vessels as per 1731, with octants not permitted until 1748.[16]

Surveying

In surveying the *Jacob's staff*, contemporaneously referred to as a *jacob staff*, is a single straight rod or staff made of nonferrous material, pointed and metal-clad at the bottom for penetrating the ground.[17] It also has a screw base and occasionally a ball joint on the mount, and is used for supporting a compass, transit, or other instrument.[18]

The term *cross-staff* may also have a different meaning in the history of surveying. While the astronomical cross-staff was used in surveying for measuring angles, two other devices referred to as a cross-staff were also employed.[19]

1. **Cross-head**, **cross-sight**, **surveyor's cross** or **cross** - a drum or box shaped device mounted on a pole. It had two sets of mutually perpendicular sights. This device was used by surveyors to measure offsets. Sophisticated versions had a compass and spirit levels on the top. The French versions were frequently eight-sided rather than round.[19]
2. **Optical square** - an improved version of the cross-head, the optical square used two mirrors at 45° to each other. This permitted the surveyor to see along both axes of the instrument at once.

Use of the Jacob's Staff as a support

In the past, many surveyor's instruments were used on a Jacob's staff. These include:

- Cross-head, cross-sight, surveyor's cross or cross
- Graphometer
- Circumferentor
- Holland circle
- Miner's dial
- Optical square
- Surveyor's Sextant
- Surveyor's target

Some devices, such as the modern optical targets for laser-based surveying, are still in common use on a Jacob's staff.

References

[1] Turner, Gerard L'E. *Antique Scientific Instruments*, Blandford Press Ltd. 1980 ISBN 0-7137-1068-3

[2] http://bibref.hebtools.com/?book=%20Gen&verse=32:11&src=HE

[3] Harriet Wynter and Anthony Turner, *Scientific Instruments*, Studio Vista, 1975, ISBN 0-289-70403-0

[4] Orion (http://www.maa.mhn.de/Maps/Stars_en/Fig/orion.html) This article indicates the three belt stars are sometimes called Jacob's Ladder or Jacob's Stick

[5] "The Mathematics of Levi ben Gershon, the Ralbag" (http://www.cs.biu.ac.il/~tsaban/Pdf/MathofLevi.pdf)

[6] David G. Krehbiel "Jacob's Staff", *Backsights*, Surveyor's Historical Society (http://www.surveyhistory.org/jacob's_staff1.htm)

[7] *The Oxford Companion to Ships and the Sea*, Peter Kemp ed., 1976 ISBN 0-586-08308-1

[8] "Important Astronomers, their Instruments and Discoveries" (http://obs.nineplanets.org/psc/hist1.html)

[9] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1

[10] Needham, Joseph. (1986). *Science and Civilization in China: Volume 3, Mathematics and the Sciences of the Heavens and the Earth*. Taipei: Caves Books Ltd. Pages 573–575.

[11] Ralf Kern: Wissenschaftliche Instrumente in ihrer Zeit. Band 1: Vom Astrolab zum mathematischen Besteck. Cologne, 2010. p. 214.

[12] Swanick, Lois Ann. *An Analysis Of Navigational Instruments In The Age Of Exploration: 15th Century To Mid-17th Century*, MA Thesis, Texas A&M University, December, 2005

[13] Bourne, William, *A Regiment for the Sea*, 1574

[14] Daumas, Maurice, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London 1989 ISBN 978-0-7134-0727-3

[15] Nicolàs de Hilster's web site (http://www.dehilster.info/instrumenten/crossstaff/index.html) Tests performed on various instruments are described. In addition, de Hilster describes the handling characteristics found by the testers on the Nav List mailing list.

[16] Bruyns, Willem Mörzer, *The Cross-staff, History and development of a navigational instrument*, Nederlandsch Historisch Sheepvaart Museum, Amsterdam, and Walburg Instituut, Zutphen, Netherlands, 1994 ISBN 90-6011-907-X

[17] Rutstrum, *The Wilderness Route Finder*, University of Minnesota Press (2000), ISBN 0-8166-3661-3, pp. 47-55, 64-72

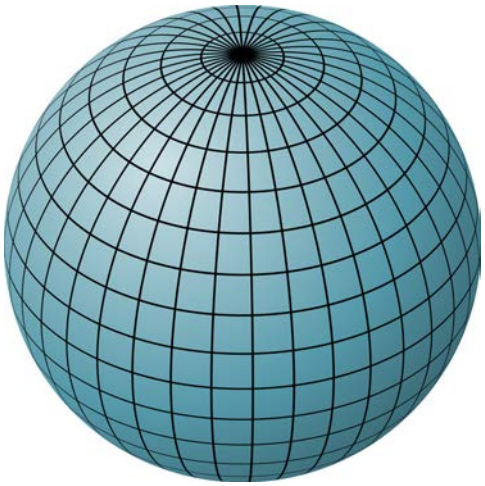
[18] Rutstrum, pp. 47-55, 64-72

[19] Turner, Gerard L'E., *Nineteenth Century Scientific Instruments*, Sotheby Publications, 1983, ISBN 0-85667-170-3

External links

- Media related to Jacob's staff at Wikimedia Commons

Latitude



A graticule on a sphere or an ellipsoid. The lines from pole to pole are lines of constant longitude, or **meridians**. The circles parallel to the equator are lines of constant latitude, or **parallels**. The graticule determines the latitude and longitude of position on the surface.

In geography, **latitude** (φ) is a geographic coordinate that specifies the north-south position of a point on the Earth's surface. Latitude is an angle (defined below) which ranges from 0° at the Equator to 90° (North or South) at the poles. Lines of constant latitude, or **parallels**, run east–west as circles parallel to the equator. Latitude is used together with longitude to specify the precise location of features on the surface of the Earth. Since the actual physical surface of the Earth is too complex for mathematical analysis, two levels of abstraction are employed in the definition of these coordinates. In the first step the physical surface is modelled by the geoid, a surface which approximates the mean sea level over the oceans and its continuation under the land masses. The second step is to approximate the geoid by a mathematically simpler reference surface. The simplest choice for the reference surface is a sphere, but the geoid is more accurately modelled by an ellipsoid. The definitions of latitude and longitude on such reference surfaces are detailed in the following sections. Lines of constant latitude and longitude together constitute a graticule on the reference surface. The latitude of a point on the *actual* surface is that of the corresponding point on the reference surface, the correspondence being along the normal to the reference surface which passes through the point on the physical surface. Latitude and longitude together with some specification of height constitute a geographic coordinate system as defined in the specification of the ISO 19111 standard.[1]

Since there are many different reference ellipsoids the latitude of a feature on the surface is not unique: this is stressed in the ISO standard which states that "without the full specification of the coordinate reference system, coordinates (that is latitude and longitude) are ambiguous at best and meaningless at worst". This is of great importance in accurate applications, such as GPS, but in common usage, where high accuracy is not required, the reference ellipsoid is not usually stated.

In English texts the latitude angle, defined below, is usually denoted by the Greek lower-case letter phi (φ or ϕ). It is measured in degrees, minutes and seconds or decimal degrees, north or south of the equator.

Measurement of latitude requires an understanding of the gravitational field of the Earth, either for setting up theodolites or for determination of GPS satellite orbits. The study of the figure of the Earth together with its gravitational field is the science of Geodesy. These topics are not discussed in this article. (See for example the textbooks by Torge[2] and Hofmann-Wellenhof and Moritz.[3])

This article relates to coordinate systems for the Earth: it may be extended to cover the Moon, planets and other celestial objects by a simple change of nomenclature.

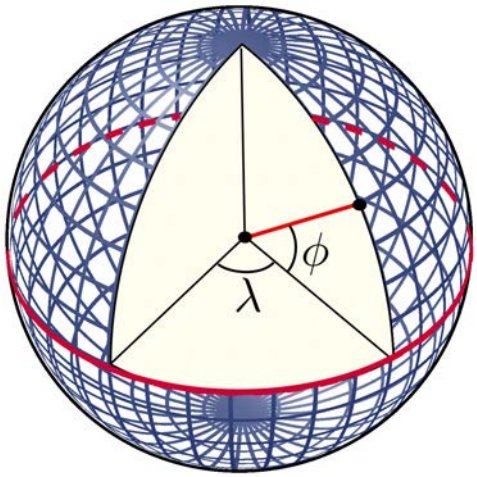
The following lists are available:

- List of countries by latitude
- List of cities by latitude

Latitude on the sphere

The graticule on the sphere

The graticule, the mesh formed by the lines of constant latitude and constant longitude, is constructed by reference to the rotation axis of the Earth. The primary reference points are the poles where the axis of rotation of the Earth intersects the reference surface. Planes which contain the rotation axis intersect the surface in the meridians and the angle between any one meridian plane and that through Greenwich (the Prime Meridian) defines the longitude: meridians are lines of constant longitude. The plane through the centre of the Earth and orthogonal to the rotation axis intersects the surface in a great circle called the equator. Planes parallel to the equatorial plane intersect the surface in circles of constant latitude; these are the parallels. The equator has a latitude of 0°, the North pole has a latitude of 90° north (written 90° N or +90°), and the South pole has a latitude of 90° south (written 90° S or −90°). The latitude of an arbitrary point is the angle between the equatorial plane and the radius to that point.

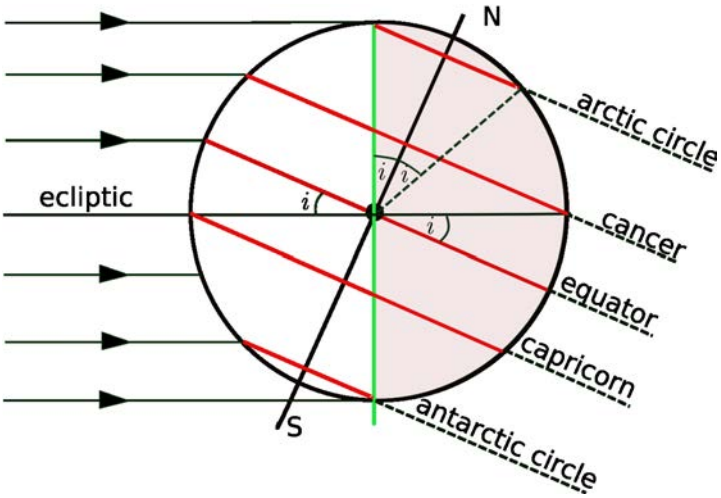


A perspective view of the Earth showing how latitude (φ) and longitude (λ) are defined on a spherical model. The graticule spacing is 10 degrees.

The latitude that is defined in this way for the sphere is often termed the spherical latitude to avoid ambiguity with auxiliary latitudes defined in subsequent sections.

Named latitudes

Besides the equator, four other parallels are of significance:



The orientation of the Earth at the December solstice.

Arctic Circle	66° 33′ 39″ N
Tropic of Cancer	23° 26′ 21″ N
Tropic of Capricorn	23° 26′ 21″ S
Antarctic Circle	66° 33′ 39" S

The plane of the Earth's orbit about the sun is called the ecliptic. The plane perpendicular to the rotation axis of the Earth is the equatorial plane. The angle between the ecliptic and the equatorial plane is called the inclination of the ecliptic, denoted by i in the figure. The current value of this angle is 23° 26′ 21″.[4] It is also called the axial tilt of the Earth since it is equal to the angle between the axis of rotation and the normal to the ecliptic.

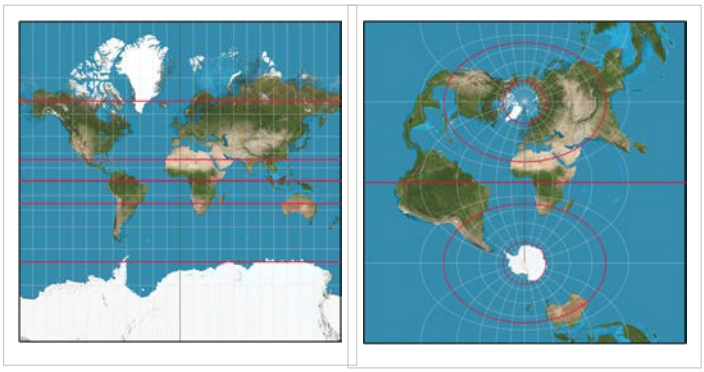
The figure shows the geometry of a cross section of the plane normal to the ecliptic and through the centres of the Earth and the Sun at the December solstice when the sun is overhead at some point of the Tropic of Capricorn. The south polar latitudes below the Antarctic Circle are in daylight whilst the north polar latitudes above the Arctic Circle are in night. The situation is reversed at the June solstice when the sun is overhead at the Tropic of Cancer. The latitudes of the tropics are equal to the inclination of the ecliptic and the polar circles are at latitudes equal to its complement. Only at latitudes in between the two tropics is it possible for the sun to be directly overhead (at the zenith).

The named parallels are clearly indicated on the Mercator projections shown below.

Map projections from the sphere

On map projections there is no simple rule as to how meridians and parallels should appear. For example, on the spherical Mercator projection the parallels are horizontal and the meridians are vertical whereas on the Transverse Mercator projection there is no correlation of parallels and meridians with horizontal and vertical, both are complicated curves. The red lines are the named latitudes of the previous section.

Normal Mercator **Transverse Mercator**



For map projections of large regions, or the whole world, a spherical Earth model is completely satisfactory since the variations attributable to ellipticity are negligible on the final printed maps.

Meridian distance on the sphere

On the sphere the normal passes through the centre and the latitude (φ) is therefore equal to the angle subtended at the centre by the meridian arc from the equator to the point concerned. If the meridian distance is denoted by *m*(φ) then

$$m(\phi) = \frac{\pi}{180} R\phi_{\text{degrees}} = R\phi_{\text{radians}}.$$

where R denotes the mean radius of the Earth. R is equal to 6371 km or 3959 miles. No higher accuracy is appropriate for R since higher precision results necessitate an ellipsoid model. With this value for R the meridian length of 1 degree of latitude on the sphere is 111.2 km or 69 miles. The length of 1 minute of latitude is 1.853 km, or 1.15 miles. (See nautical mile).

Latitude on the ellipsoid

Ellipsoids

In 1687 Isaac Newton published the Principia in which he proved that a rotating self-gravitating fluid body in equilibrium takes the form of an oblate ellipsoid.[5] (This article uses the term ellipsoid in preference to the older term *spheroid*). Newton's result was confirmed by geodetic measurements in the eighteenth century. (See Meridian arc.) An oblate ellipsoid is the three dimensional surface generated by the rotation of an ellipse about its shorter axis (minor axis). 'Oblate ellipsoid of revolution' is abbreviated to **ellipsoid** in the remainder of this article. (Ellipsoids which do not have an axis of symmetry are termed tri-axial.)

Many different reference ellipsoids have been used in the history of geodesy. In pre-satellite days they were devised to give a good fit to the geoid over the limited area of a survey but, with the advent of GPS, it has become natural to use reference ellipsoids (such as WGS84) with centres at the centre of mass of the Earth and minor axis aligned to the rotation axis of the Earth. These geocentric ellipsoids are usually within 100m of the geoid. Since latitude is defined with respect to an ellipsoid, the position of a given point is different on each ellipsoid: one can't exactly specify the latitude and longitude of a geographical feature without specifying the ellipsoid used. Many maps maintained by national agencies are based on older ellipsoids so it is necessary to know how the latitude and longitude values are transformed from one ellipsoid to another. GPS handsets include software to carry out datum transformations which link WGS84 to the local reference ellipsoid with its associated grid.

The geometry of the ellipsoid

The shape of an ellipsoid of revolution is determined by the shape of the ellipse which is rotated about its minor (shorter) axis. Two parameters are required. One is invariably the equatorial radius, which is the semi-major axis, *a*. The other parameter is usually (1) the polar radius or semi-minor axis, *b*; or (2) the (first) flattening, *f*; or (3) the eccentricity, *e*. These parameters are not independent: they are related by

$$f = \frac{a-b}{a}, \qquad e^2 = 2f - f^2, \qquad b = a(1-f) = a\sqrt{1-e^2}.$$

Many other parameters (see ellipse, ellipsoid) appear in the study of geodesy, geophysics and map projections but they can all be expressed in terms of one or two members of the set *a*, *b*, *f* and *e*. Both *f* and *e* are small and often appear in series expansions in calculations; they are of the order 1/300 and 0.08 respectively. Values for a number of ellipsoids are given in Figure of the Earth. Reference ellipsoids are usually defined by the semi-major axis and the *inverse* flattening, *1/f*. For example, the defining values for the WGS84 ellipsoid, used by all GPS devices, are[6]

- *a* (equatorial radius): 6,378,137.0 m exactly
- *1/f* (inverse flattening): 298.257,223,563 exactly

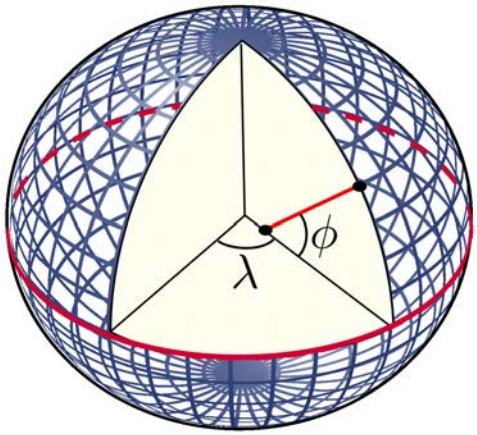
from which are derived

- b (polar radius): 6,356,752.3142 m
- e^2 (eccentricity squared): 0.006,694,379,990,14

The difference of the major and minor semi-axes is about 21 km and as fraction of the semi-major axis it equals the flattening; on a computer the ellipsoid could be sized as 300px by 299px. This would be indistinguishable from a sphere shown as 300px by 300px, so illustrations always exaggerate the flattening.

Geodetic and geocentric latitudes

The graticule on the ellipsoid is constructed in exactly the same way as on the sphere. The normal at a point on the surface of an ellipsoid does not pass through the centre, except for points on the equator or at the poles, but the definition of latitude remains unchanged as the angle between the normal and the equatorial plane. The terminology for latitude must be made more precise by distinguishing



The definition of geodetic latitude (φ) and longitude (λ) on an ellipsoid. The normal to the surface does not pass through the centre, except at the equator and at the poles.

Geodetic latitude: the angle between the normal and the equatorial plane. The standard notation in English publications is φ. This is the definition assumed when the word latitude is used without qualification. The definition must be accompanied with a specification of the ellipsoid.

Geocentric latitude: the angle between the radius (from centre to the point on the surface) and the equatorial plane. (Figure below). There is no standard notation: examples from various texts include ψ, q, φ', φ_c, φ_g. This article uses ψ.

Spherical latitude: the angle between the normal to a spherical reference surface and the equatorial plane.

Geographic latitude must be used with care. Some authors use it as a synonym for geodetic latitude whilst others use it as an alternative to the astronomical latitude.

Latitude (unqualified) should normally refer to the geodetic latitude.

The importance of specifying the reference datum may be illustrated by a simple example. On the reference ellipsoid for WGS84, the centre of the Eiffel Tower has a geodetic latitude of 48° 51′ 29″ N, or 48.8583° N and longitude of 2° 17′ 40″ E or 2.2944°E. The same coordinates on the datum ED50 define a point on the ground which is 140 m distant from Tower. A web search may produce several different values for the latitude of the Tower; the reference ellipsoid is rarely specified.

The length of a degree of latitude

In Meridian arc and standard texts[2][7][8] it is shown that the distance along a meridian from latitude φ to the equator is given by (φ in radians)

$$m(\phi) = \int_0^{\phi} M(\phi) d\phi = a(1-e^2) \int_0^{\phi} \left(1 - e^2 \sin^2 \phi\right)^{-3/2} d\phi$$

The function $M(\phi)$in the first integral is the meridional radius of curvature.

The distance from the equator to the pole is

$$m_p = m(\pi/2)$$

For WGS84 this distance is 10001.965729 km.

The evaluation of the meridian distance integral is central to many studies in geodesy and map projection. It can be evaluated by expanding the integral by the binomial series and integrating term by term: see Meridian arc for details.

The length of the meridian arc between two given latitudes is given by replacing the limits of the integral by the latitudes concerned. The length of a *small* meridian arc is given by [7][8]

$$\delta m(\phi) = M(\phi)\delta\phi = a(1-e^2)\left(1-e^2\sin^2\phi\right)^{-3/2}\delta\phi$$

ϕ	Δ^1_{LAT}	Δ^1_{LONG}
0°	110.574 km	111.320 km
15°	110.649 km	107.551 km
30°	110.852 km	96.486 km
45°	111.132 km	78.847 km
60°	111.412 km	55.800 km
75°	111.618 km	28.902 km
90°	111.694 km	0.000 km

When the latitude difference is 1 degree, corresponding to π /180 radians, the arc distance is about

$$\Delta^1_{\mathrm{LAT}} = \frac{\pi a(1-e^2)}{180(1-e^2\sin^2\phi)^{3/2}}$$

The distance in metres (correct to 0.01 metre) between latitudes ($\phi - 0.5$deg) and ($\phi + 0.5$deg) on the WGS84 spheroid is

$$\Delta^1_{\mathrm{LAT}} = 111132.954 - 559.822\cos 2\phi + 1.175\cos 4\phi$$

The variation of this distance with latitude (on WGS84) is shown in the table along with the length of a degree of longitude:

$$\Delta^1_{\mathrm{LONG}} = \frac{\pi a\cos\phi}{180(1-e^2\sin^2\phi)^{1/2}}$$

A calculator for any latitude is provided by (a) the U.S. government's National Geospatial-Intelligence Agency(NGA),[9] (b) CSGnet[10]

Auxiliary latitudes

There are six **auxiliary latitudes** that have applications to special problems in geodesy, geophysics and the theory of map projections:

- geocentric latitude,
- reduced (or parametric) latitude,
- rectifying latitude,
- authalic latitude,
- conformal latitude,
- isometric latitude.

The definitions given in this section all relate to locations on the reference ellipsoid but the first two auxiliary latitudes, like the geodetic latitude, can be extended to define a three dimensional geographic coordinate system as discussed below. The remaining latitudes are not used in this way; they are used *only* as intermediate constructs in map projections of the reference ellipsoid to the plane or in calculations of geodesics on the ellipsoid. Their numerical values are not of interest. For example no one would need to calculate the authalic latitude of the Eiffel Tower.

The expressions below give the auxiliary latitudes in terms of the geodetic latitude, the semi-major axis, *a*, and the eccentricity, *e*. (For inverses see below.) The forms given are, apart from notational variants, those in the standard reference for map projections, namely "Map projections — a working manual" by J.P.Snyder.[11] Derivations of

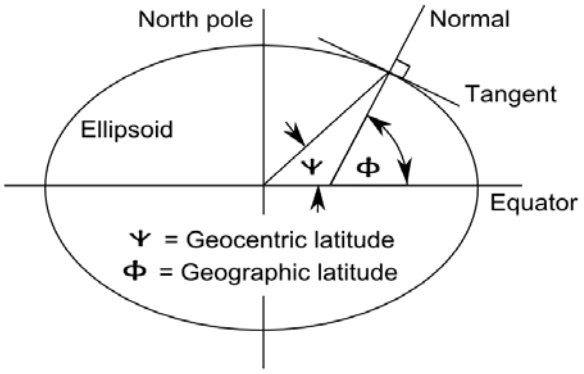
these expressions may be found in Adams[12] and web publications by Osborne[7] and Rapp[8].

Geocentric latitude

The **geocentric latitude** is the angle between the equatorial plane and the radius from the centre to a point on the surface. The relation between the geocentric latitude (ψ) and the geodetic latitude (φ) is derived in the above references as

$$\psi(\phi) = \tan^{-1}\left[(1-e^2)\tan\phi\right] .$$

The geodetic and geocentric latitudes are equal at the equator and poles. The value of the squared eccentricity is approximately 0.007 (depending on the choice of ellipsoid) and the maximum difference of (φ-ψ) is approximately 11.5 minutes of arc at a geodetic latitude of 45°5′.



The definition of geodetic (or geographic) and geocentric latitudes.

Reduced (or parametric) latitude

The **reduced** or **parametric latitude**, β, is defined by the radius drawn from the centre of the ellipsoid to that point Q on the surrounding sphere (of radius *a*) which is the projection parallel to the Earth's axis of a point P on the ellipsoid at latitude ϕ. It was introduced by Legendre[13] and Bessel[14] who solved problems for geodesics on the ellipsoid by transforming them to an equivalent problem for spherical geodesics by using this smaller latitude. Bessel's notation, $u(\phi)$, is also used in the current literature. The reduced latitude is related to the geodetic latitude by[8][7]

$$\beta(\phi) = \tan^{-1}\left[\sqrt{1-e^2}\tan\phi\right]$$

The alternative name arises from the parameterization of the equation of the ellipse describing a meridian section. In terms of Cartesian coordinates *p*, the distance from the minor axis, and *z*, the distance above the equatorial plane, the equation of the ellipse is

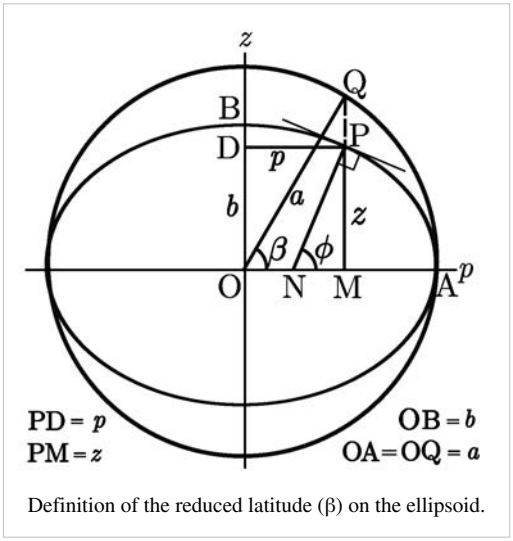
$$\frac{p^2}{a^2} + \frac{z^2}{b^2} = 1.$$

The Cartesian coordinates of the point are parameterized by

$$p = a\cos\beta, \qquad z = b\sin\beta;$$

Cayley[15] suggested the term *parametric latitude* because of the form of these equations.

The reduced latitude is not used in the theory of map projections. Its most important application is in the theory of ellipsoid geodesics. (Vincenty, Karney[16]).



Definition of the reduced latitude (β) on the ellipsoid.

Rectifying latitude

The **rectifying latitude**, μ, is the meridian distance scaled so that its value at the poles is equal to 90 degrees or π/2 radians:

$$\mu(\phi) = \frac{\pi}{2}\frac{m(\phi)}{m_p}$$

where the meridian distance from the equator to a latitude φ is (see Meridian arc)

$$m(\phi) = a(1-e^2)\int_0^\phi \left(1-e^2\sin^2\phi\right)^{-3/2}\,d\phi,$$

and the length of the meridian quadrant from the equator to the pole is

$$m_p = m(\pi/2).$$

Using the rectifying latitude to define a latitude on a sphere of radius

$$R = \frac{2m_p}{\pi}$$

defines a projection from the ellipsoid to the sphere such that all meridians have true length and uniform scale. The sphere may then be projected to the plane with an equirectangular projection to give a double projection from the ellipsoid to the plane such that all meridians have true length and uniform meridian scale. An example of the use of the rectifying latitude is the Equidistant conic projection. (Snyder,[11] Section 16). The rectifying latitude is also of great importance in the construction of the Transverse Mercator projection.

Authalic latitude

The **authalic** (Greek for same area) latitude, ξ, gives an area-preserving transformation to a sphere.

$$\xi(\phi) = \sin^{-1}\left(\frac{q(\phi)}{q_p}\right)$$

where

$$\begin{aligned} q(\phi) &= \frac{(1-e^2)\sin\phi}{1-e^2\sin^2\phi} - \frac{1-e^2}{2e}\ln\left(\frac{1-e\sin\phi}{1+e\sin\phi}\right), \\ &= \frac{(1-e^2)\sin\phi}{1-e^2\sin^2\phi} + \frac{1-e^2}{e}\tanh^{-1}(e\sin\phi), \end{aligned}$$

and

$$q_p = q(\pi/2) = 1 - \frac{1-e^2}{2e}\ln\left(\frac{1-e}{1+e}\right) = 1 + \frac{1-e^2}{e}\tanh^{-1}e,$$

and the radius of the sphere is taken as

$$R_q = a\sqrt{q_p/2}.$$

An example of the use of the authalic latitude is the Albers equal-area conic projection. (Snyder,[11] Section 14).

Conformal latitude

The **conformal latitude**, χ, gives an angle-preserving (conformal) transformation to the sphere.

$$\begin{aligned}\chi(\phi) &= 2\tan^{-1}\left[\left(\frac{1+\sin\phi}{1-\sin\phi}\right)\left(\frac{1-e\sin\phi}{1+e\sin\phi}\right)^{e}\right]^{1/2} - \frac{\pi}{2} \\ &= 2\tan^{-1}\left[\tan\left(\frac{\phi}{2}+\frac{\pi}{4}\right)\left(\frac{1-e\sin\phi}{1+e\sin\phi}\right)^{e/2}\right] - \frac{\pi}{2}\ , \\ &= \sin^{-1}\left[\tanh\left(\tanh^{-1}(\sin\phi) - e\tanh^{-1}(e\sin\phi)\right)\right] \\ &= \operatorname{gd}\left[\operatorname{gd}^{-1}(\phi) - e\tanh^{-1}(e\sin\phi)\right].\end{aligned}$$

where gd(*x*) is the Gudermannian function. (See also Mercator projection.) The conformal latitude defines a transformation from the ellipsoid to a sphere of *arbitrary* radius such that the angle of intersection between any two lines on the ellipsoid is the same as the corresponding angle on the sphere (so that the shape of *small* elements is well preserved). A further conformal transformation from the sphere to the plane gives a conformal double projection from the ellipsoid to the plane. This is not the only way of generating such a conformal projection. For example, the 'exact' version of the Transverse Mercator projection on the ellipsoid is not a double projection. (It does, however, involve a generalisation of the conformal latitude to the complex plane).

Isometric latitude

The **isometric latitude** is conventionally denoted by ψ (not to be confused with the geocentric latitude): it is used in the development of the ellipsoidal versions of the normal Mercator projection and the Transverse Mercator projection. The name "isometric" arises from the fact that at any point on the ellipsoid equal increments of ψ and longitude λ give rise to equal distance displacements along the meridians and parallels respectively. The graticule defined by the lines of constant ψ and constant λ, divides the surface of the ellipsoid into a mesh of squares (of varying size). The isometric latitude is zero at the equator but rapidly diverges from the geodetic latitude, tending to infinity at the poles. The conventional notation is given in Snyder[11] (page 15):

$$\begin{aligned}\psi(\phi) &= \ln\left[\tan\left(\frac{\pi}{4}+\frac{\phi}{2}\right)\right] + \frac{e}{2}\ln\left[\frac{1-e\sin\phi}{1+e\sin\phi}\right] \\ &= \tanh^{-1}(\sin\phi) - e\tanh^{-1}(e\sin\phi) \\ &= \operatorname{gd}^{-1}(\phi) - e\tanh^{-1}(e\sin\phi).\end{aligned}$$

For the *normal* Mercator projection (on the ellipsoid) this function defines the spacing of the parallels: if the length of the equator on the projection is E (units of length or pixels) then the distance, *y*, of a parallel of latitude φ from the equator is

$$y(\phi) = \frac{E}{2\pi}\psi(\phi).$$

The isometric latitude is closely related to the conformal latitude:

$$\psi(\phi) = \operatorname{gd}^{-1}\chi(\phi).$$

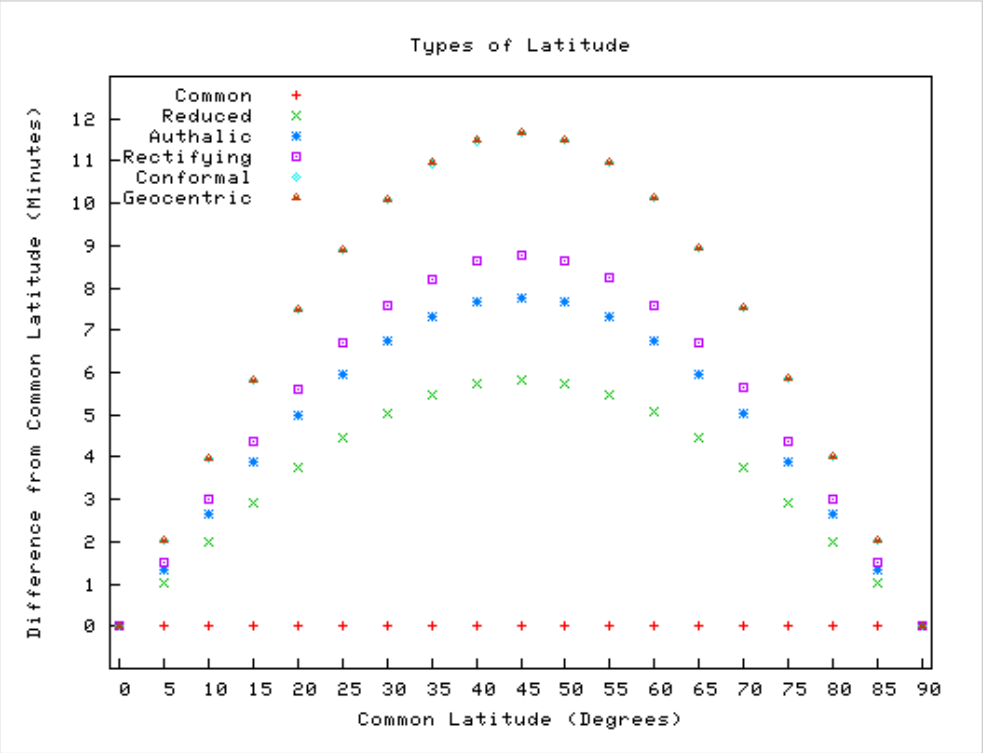
Inverse formulae and series

The formulae in the previous sections give the auxiliary latitude in terms of the geodetic latitude. The expressions for the geocentric and reduced latitudes may be inverted directly but this is impossible in the four remaining cases: the rectifying, authalic, conformal and isometric latitudes. There are two methods of proceeding. The first is a numerical inversion of the defining equation for each and every particular value of the auxiliary latitude. The methods available are fixed-point iteration and Newton-Raphson root finding. The other, more useful, approach is to express the auxiliary latitude as a series in terms of the geodetic latitude and then invert the series by the method of Lagrange

reversion. Such series are presented by Adams[12] who uses Taylor series expansions and gives coefficients in terms of the eccentricity. Osborne[7] derives series to arbitrary order by using the computer algebra package Maxima[17] and expresses the coefficients in terms of both eccentricity and flattening. The series method is not applicable to the isometric latitude and one must use the conformal latitude in an intermediate step.

Numerical comparison of auxiliary latitudes

The following plot shows the magnitude of the difference between the geodetic latitude, (denoted as the 'common' latitude on the plot), and the auxiliary latitudes other than the isometric latitude (which diverges to infinity at the poles). In every case the geodetic latitude is the greater. The differences shown on the plot are in arc minutes. The horizontal resolution of the plot fails to make clear that the maxima of the curves are not at 45° but calculation shows that they are within a few arc minutes of 45°. Some representative data points are given in the table following the plot. Note the closeness of the conformal and geocentric latitudes. This was exploited in the days of hand calculators to expedite the construction of map projections. (Snyder,[11] page 108).



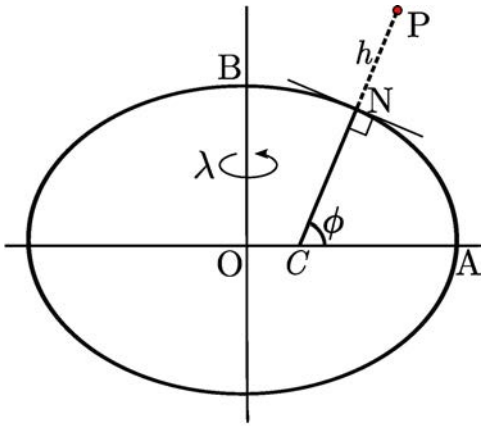
Approximate difference from geodetic latitude (ϕ)					
ϕ	**Reduced** $\phi - \beta$	**Authalic** $\phi - \xi$	**Rectifying** $\phi - \mu$	**Conformal** $\phi - \chi$	**Geocentric** $\phi - \psi$
0°	0.00′	0.00′	0.00′	0.00′	0.00′
15°	2.91′	3.89′	4.37′	5.82′	5.82′
30°	5.05′	6.73′	7.57′	10.09′	10.09′
45°	5.84′	7.78′	8.76′	11.67′	11.67′
60°	5.06′	6.75′	7.59′	10.12′	10.13′
75°	2.92′	3.90′	4.39′	5.85′	5.85′
90°	0.00′	0.00′	0.00′	0.00′	0.00′

Latitude and coordinate systems

The geodetic latitude, or any of the auxiliary latitudes defined on the reference ellipsoid, constitutes with longitude a two-dimensional coordinate system on that ellipsoid. To define the position of an arbitrary point it is necessary to extend such a coordinate system into three dimensions. Three latitudes are used in this way: the geodetic, geocentric and reduced latitudes are used in geodetic coordinates, spherical polar coordinates and ellipsoidal coordinates respectively.

Geodetic coordinates

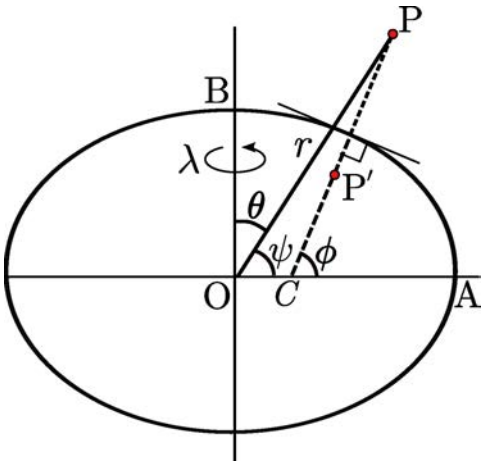
At an arbitrary point P consider the line PN which is normal to the reference ellipsoid. The geodetic coordinates P(ϕ,λ,h) are the latitude and longitude of the point N on the ellipsoid and the distance PN. This height differs from the height above the geoid or a reference height such as that above mean sea level at a specified location. The direction of PN will also differ from the direction of a vertical plumb line. The relation of these different heights requires knowledge of the shape of the geoid and also the gravity field of the Earth.



Geodetic coordinates P(ϕ,λ,h)

Spherical polar coordinates

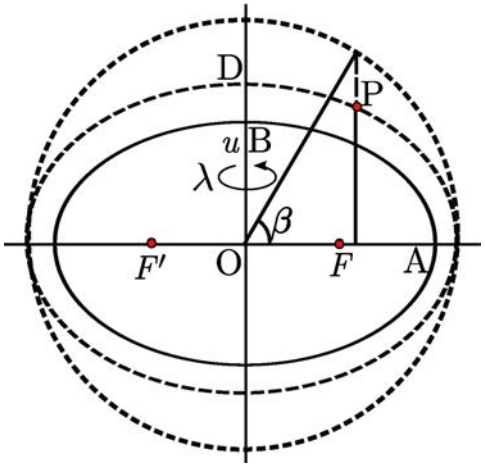
The geocentric latitude ψ is the complement of the polar angle θ in conventional spherical polar coordinates in which the coordinates of a point are P(r, θ, λ) where r is the distance of P from the centre O, θ is the angle between the radius vector and the polar axis andλ is longitude. Since the normal at a general point on the ellipsoid does not pass through the centre it is clear that points on the normal, which all have the same geodetic latitude, will have differing geocentic latitudes. Spherical polar coordinate systems are used in the analysis of the gravity field.



Geocentric coordinate related to spherical polar coordinates P(r, θ, λ)

Ellipsoidal coordinates

The reduced latitude can also be extended to a three dimensional coordinate system. For a point P not on the reference ellipsoid (semi-axes OA and OB) construct an auxiliary ellipsoid which is confocal (same foci F, F') with the reference ellipsoid: the necessary condition is that the product *ae* of semi-major axis and eccentricity is the same for both ellipsoids. Let *u* be the semi-minor axis (OD) of the auxiliary ellipsoid. Further let β be the reduced latitude of P on the auxiliary ellipsoid. The set (*u*,β,λ) define the ellipsoid coordinates. (Torge[2] Section 4.2.2). These coordinates are the natural choice in models of the gravity field for a uniform distribution of mass bounded by the reference ellipsoid.



Ellipsoidal coordinates P(*u*,β,λ)

Coordinate conversions

The relations between the above coordinate systems, and also Cartesian coordinates are not presented here. The transformation between geodetic and Cartesian coordinates may be found in Geodetic system. The relation of Cartesian and spherical polars is given in Spherical coordinate system. The relation of Cartesian and ellipsoidal coordinates is discussed in Torge.[2]

Astronomical latitude

Astronomical latitude (Φ) is the angle between the equatorial plane and the true vertical at a point on the surface: the true vertical, the direction of a plumb line, is the direction of the **gravity field** at that point. (The gravity field is the resultant of the gravitational acceleration and the centrifugal acceleration at that point. See Torge.[2]) Astronomic latitude is calculated from angles measured between the zenith and stars whose declination is accurately known.

In general the true vertical at a point on the surface does not exactly coincide with either the normal to the reference ellipsoid or the normal to the geoid. The angle between the astronomic and geodetic normals is usually a few seconds of arc but it is important in geodesy.[2][3]

Astronomical latitude is not to be confused with declination, the coordinate astronomers used in a similar way to describe the locations of stars north/south of the celestial equator (see equatorial coordinates), nor with ecliptic latitude, the coordinate that astronomers use to describe the locations of stars north/south of the ecliptic (see ecliptic coordinates).

Footnotes

[1] The current full documentation of ISO 19111 may be purchased from http://www.iso.org but drafts of the final standard are freely available at many web sites, one such is available at CSIRO (https://www.seegrid.csiro.au/wiki/pub/Xmml/CoordinateReferenceSystems/19111_FDIS20021107.pdf)

[2] Torge, W (2001) Geodesy (3rd edition), published by de Gruyter, isbn=3-11-017072-8

[3] Hofmann-Wellenhof, B and Moritz, H (2006). 'Physical Geodesy (second edition)' ISBN3211-33544-7.

[4] The Astronomical Almanac published annually by the National Almanac Office in the United States (http://asa.usno.navy.mil/) and the United Kingdom (http://astro.ukho.gov.uk/nao/publicat/asa.html).

[5] Isaac Newton:*Principia* Book III Proposition XIX Problem III, p. 407 in Andrew Motte translation, available on line at (http://www.archive.org)

[6] The WGS84 parameters are listed in the National Geospatial-Intelligence Agency publication TR8350.2 (http://earth-info.nga.mil/GandG/publications/tr8350.2/tr8350_2.htmlNIMA) page 3-1.

[7] Osborne, P (2013) The Mercator Projections (http://mercator.myzen.co.uk/mercator.pdf) (Chapters 5,6)

[8] Rapp, Richard H. (1991). *Geometric Geodesy, Part I*, Dept. of Geodetic Science and Surveying, Ohio State Univ., Columbus, Ohio. (http://hdl.handle.net/1811/24333)(Chapter 3)

[9] Length of degree calculator - National Geospatial-Intelligence Agency (http://msi.nga.mil/MSISiteContent/StaticFiles/Calculators/degree.html)

[10] http://www.csgnetwork.com/degreelenllavcalc.html

[11] This paper can be downloaded from USGS pages. (http://pubs.er.usgs.gov/pubs/pp/pp1395)

[12] Adams, Oscar S (1921). *Latitude Developments Connected With Geodesy and Cartography, (with tables, including a table for Lambert equal area meridional projection)*. Special Publication No. 67 of the US Coast and Geodetic Survey. A facsimile of this publication is available from the US National Oceanic and Atmospheric Administration (NOAA) at http://docs.lib.noaa.gov/rescue/cgs_specpubs/QB275U35no671921.pdf **Warning**: Adams uses the nomenclature isometric latitude for the conformal latitude of this article.

[13] A. M. Legendre, 1806, Analyse des triangles tracés sur la surface d'un sphéroïde, Mém. de l'Inst. Nat. de France, 130--161 (1st semester).

[14] F. W. Bessel, 1825, Uber die Berechnung der geographischen Langen und Breiten aus geodatischen Vermessungen, Astron.Nachr., 4(86), 241-254, , translated into English by C. F. F. Karney and R. E. Deakin as The calculation of longitude and latitude from geodesic measurements, Astron. Nachr. 331(8), 852-861 (2010), E-print , http://adsabs.harvard.edu/abs/1825AN.....4..241B.

[15] A. Cayley, 1870, On the geodesic lines on an oblate spheroid, Phil. Mag. 40 (4th ser.), 329-340.

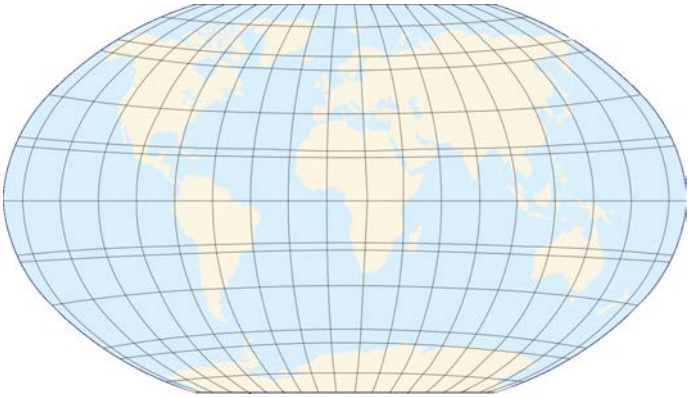
[16] C. F. F. Karney (2013), Algorithms for geodesics, J. Geodesy **87**(1), 43–55, DOI: 10.1007/s00190-012-0578-z (http://dx.doi.org/10.1007/s00190-012-0578-z).

[17] Maxima computer algebra system (http://maxima.sourceforge.net/)

External links

- A Comprehensive Library of Cartographic Projection Functions (Preliminary Draft) (http://web.archive.org/web/20080625111630/http://members.verizon.net/~vze2hc4d/proj4/manual.pdf) at the Internet ArchivePDF (1.88 MB)
- GEONets Names Server (http://earth-info.nga.mil/gns/html/), access to the National Geospatial-Intelligence Agency's (NGA) database of foreign geographic feature names.
- Look-up Latitude and Longitude (http://www.bcca.org/misc/qiblih/latlong.html)
- Resources for determining your latitude and longitude (http://jan.ucc.nau.edu/~cvm/latlon_find_location.html)
- Convert decimal degrees into degrees, minutes, seconds (http://geography.about.com/library/howto/htdegrees.htm) - Info about decimal to sexagesimal conversion
- Convert decimal degrees into degrees, minutes, seconds (http://www.fcc.gov/mb/audio/bickel/DDDMMSS-decimal.html)
- Distance calculation based on latitude and longitude (http://www.marinewaypoints.com/learn/greatcircle.shtml) - JavaScript version
- Zoomable version of the map (https://www.cia.gov/library/publications/the-world-factbook/graphics/ref_maps/pdf/political_world.pdf) PDF (3.47 MB)
- Determination of Latitude by Francis Drake on the Coast of California in 1579 (http://www.longcamp.com/nav.html)
- Longitude and Latitude of Points of Interest (http://www.thegpscoordinates.com)
- Length Of A Degree Of Latitude And Longitude Calculator (http://www.csgnetwork.com/degreelenllavcalc.html)

Longitude



Map of Earth

Longitude (λ)

Lines of longitude appear vertical with varying curvature in this projection, but are actually halves of great ellipses, with identical radii at a given latitude.

Latitude (φ)

Lines of latitude appear horizontal with varying curvature in this projection; but are actually circular with different radii. All locations with a given latitude are collectively referred to as a circle of latitude.

The **equator** divides the planet into a Northern Hemisphere and a Southern Hemisphere, and has a latitude of 0°.

Geodesy
Fundamentals
• Geodesy • Geodynamics • Geomatics • Cartography
Concepts
• Datum • Distance • Geoid • Fig. Earth • Geodetic system • Geodesic • Geog. coord. system • Hor. pos. represent. • Lat. / Long. • Map proj. • Ref. ellipsoid • Satellite geodesy • Spatial ref. system
Technologies
• GNSS • GPS • GLONASS • Galileo • IRNSS • Compass
Standards
• ED50 • ETRS89 • GRS 80 • NAD83 • NAVD88 • SAD69 • SRID • UTM • WGS84
History
• History of geodesy • NAVD29

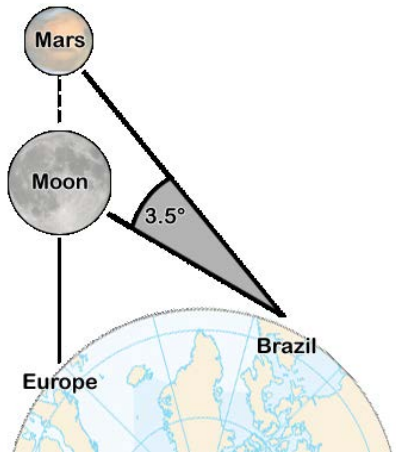
Longitude (/ˈlɒndʒɪtjuːd/ or /ˈlɒŋgɪtjuːd/),[1] is a geographic coordinate that specifies the east-west position of a point on the Earth's surface. It is an angular measurement, usually expressed in degrees and denoted by the Greek letter lambda (λ). Points with the same longitude lie in lines running from the North Pole to the South Pole. By convention, one of these, the Prime Meridian, which passes through the Royal Observatory, Greenwich, England, establishes the position of zero degrees longitude. The longitude of other places is measured as an angle east or west from the Prime Meridian, ranging from 0° at the Prime Meridian to +180° eastward and −180° westward.

Specifically, it is the angle between a plane containing the Prime Meridian and a plane containing the North Pole, South Pole and the location in question. This forms a right-handed coordinate system with the z axis (right hand thumb) pointing from the Earth's center toward the North Pole and the x axis (right hand index finger) extending from Earth's center through the equator at the Prime Meridian.

A location's north-south position along a meridian is given by its latitude, which is (not quite exactly) the angle between the local vertical and the plane of the Equator.

If the Earth were perfectly spherical and homogeneous, then longitude at a point would just be the angle between a vertical north-south plane through that point and the plane of the Greenwich meridian. Everywhere on Earth the vertical north-south plane would contain the Earth's axis. But the Earth is not homogenous, and has mountains—which have gravity and so can shift the vertical plane away from the Earth's axis. The vertical north-south plane still intersects the plane of the Greenwich meridian at some angle; that angle is astronomical longitude, the longitude you calculate from star observations. The longitude shown on maps and GPS devices is the angle between the Greenwich plane and a not-quite-vertical plane through the point; the not-quite-vertical plane is perpendicular to the surface of the spheroid chosen to approximate the Earth's sea-level surface, rather than perpendicular to the sea-level surface itself.

History



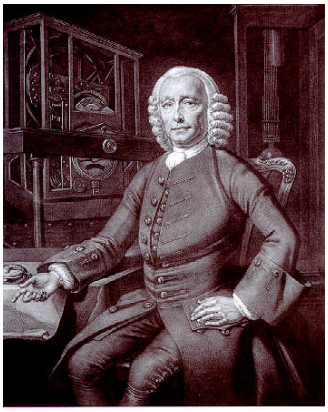
Amerigo Vespucci's means of determining longitude

The measurement of longitude is important both to cartography and to provide safe ocean navigation. Mariners and explorers for most of history struggled to determine precise longitude. Finding a method of determining exact longitude took centuries, resulting in the history of longitude recording the effort of some of the greatest scientific minds.

Latitude was calculated by observing with quadrant or astrolabe the inclination of the sun or of charted stars, but longitude presented no such manifest means of study.

Amerigo Vespucci was perhaps the first European to proffer a solution, after devoting a great deal of time and energy studying the problem during his sojourns in the New World:

> *As to longitude, I declare that I found so much difficulty in determining it that I was put to great pains to ascertain the east-west distance I had covered. The final result of my labours was that I found nothing better to do than to watch for and take observations at night of the conjunction of one planet with another, and especially of the conjunction of the moon with the other planets, because the moon is swifter in her course than any other planet. I compared my observations with an almanac. After I had made experiments many nights, one night, the twenty-third of August 1499, there was a conjunction of the moon with Mars, which according to the almanac was to occur at midnight or a half hour before. I found that...at midnight Mars's position was three and a half degrees to the east.*[2]

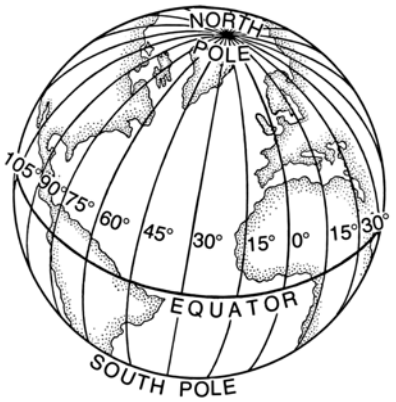


John Harrison solved the greatest problem of his day.[3]

By comparing the relative positions of the moon and Mars with their anticipated positions, Vespucci was able to crudely deduce his longitude. But this method had several limitations: First, it required the occurrence of a specific astronomical event (in this case, Mars passing through the same right ascension as the moon), and the observer needed to anticipate this event via an astronomical almanac. One needed also to know the precise time, which was difficult to ascertain in foreign lands. Finally, it required a stable viewing platform, rendering the technique useless on the rolling deck of a ship at sea. See Lunar distance (navigation).

In 1612, Galileo Galilei proposed that with sufficiently accurate knowledge of the orbits of the moons of Jupiter one could use their positions as a universal clock and this would make possible the determination of longitude, but the method he devised was impracticable and it was never used at sea. In the early 18th century there were several maritime disasters attributable to serious errors in reckoning position at sea, such as the loss of four ships of the fleet of Sir Cloudesley Shovell in the Scilly naval disaster of 1707. Motivated by these disasters, in 1714 the British government established the Board of Longitude: prizes were to be awarded to the first person to demonstrate a practical method for determining the longitude of a ship at sea. These prizes motivated many to search for a solution.

John Harrison, a self-educated English clockmaker then invented the marine chronometer, a key piece in solving the problem of accurately establishing longitude at sea, thus revolutionising and extending the possibility of safe long distance sea travel.[3] Though the British rewarded John Harrison for his marine chronometer in 1773, chronometers remained very expensive and the lunar distance method continued to be used for decades. Finally, the combination of the availability of marine chronometers and wireless telegraph time signals put an end to the use of lunars in the 20th century.



Drawing of Earth with Longitudes

Unlike latitude, which has the equator as a natural starting position, there is no natural starting position for longitude. Therefore, a reference meridian had to be chosen. It was a popular practice to use a nation's capital as the starting point, but other significant locations were also used. While British cartographers had long used the Greenwich meridian in London, other references were used elsewhere, including: El Hierro, Rome, Copenhagen, Jerusalem, Saint Petersburg, Pisa, Paris, Philadelphia, Pennsylvania, and Washington D.C. In 1884, the International Meridian Conference adopted the Greenwich meridian as the *universal Prime Meridian* or *zero point of longitude*.

Noting and calculating longitude

Longitude is given as an angular measurement ranging from 0° at the Prime Meridian to +180° eastward and −180° westward. The Greek letter λ (lambda),[4][5] is used to denote the location of a place on Earth east or west of the Prime Meridian.

Each degree of longitude is sub-divided into 60 minutes, each of which is divided into 60 seconds. A longitude is thus specified in sexagesimal notation as *23° 27′ 30″ E*. For higher precision, the seconds are specified with a decimal fraction. An alternative representation uses degrees and minutes, where parts of a minute are expressed in decimal notation with a fraction, thus: *23° 27.500′ E*. Degrees may also be expressed as a decimal fraction: *23.45833° E*. For calculations, the angular measure may be converted to radians, so longitude may also be expressed

in this manner as a signed fraction of π (pi), or an unsigned fraction of 2π.

For calculations, the West/East suffix is replaced by a negative sign in the western hemisphere. Confusingly, the convention of negative for East is also sometimes seen. The preferred convention—that East be positive—is consistent with a right-handed Cartesian coordinate system, with the North Pole up. A specific longitude may then be combined with a specific latitude (usually positive in the northern hemisphere) to give a precise position on the Earth's surface.

Longitude at a point may be determined by calculating the time difference between that at its location and Coordinated Universal Time (UTC). Since there are 24 hours in a day and 360 degrees in a circle, the sun moves across the sky at a rate of 15 degrees per hour (360°/24 hours = 15° per hour). So if the time zone a person is in is three hours ahead of UTC then that person is near 45° longitude (3 hours × 15° per hour = 45°). The word *near* was used because the point might not be at the center of the time zone; also the time zones are defined politically, so their centers and boundaries often do not lie on meridians at multiples of 15°. In order to perform this calculation, however, a person needs to have a chronometer (watch) set to UTC and needs to determine local time by solar or astronomical observation. The details are more complex than described here: see the articles on Universal Time and on the equation of time for more details.

Singularity and discontinuity of longitude

Note that the longitude is singular at the Poles and calculations that are sufficiently accurate for other positions, may be inaccurate at or near the Poles. Also the discontinuity at the ±180° meridian must be handled with care in calculations. An example is a calculation of east displacement by subtracting two longitudes, which gives the wrong answer if the two positions are on either side of this meridian. To avoid these complexities, consider replacing latitude and longitude with another horizontal position representation in calculation.

Plate movement and longitude

The Earth's tectonic plates move relative to one another in different directions at speeds on the order of 50 to 100mm per year.[6] So points on the Earth's surface on different plates are always in motion relative to one another, for example, the longitudinal difference between a point on the Equator in Uganda, on the African Plate, and a point on the Equator in Ecuador, on the South American Plate, is increasing by about 0.0014 arcseconds per year. These tectonic movements likewise affect latitude.

If a global reference frame such as WGS84 is used, the longitude of a place on the surface will change from year to year. To minimize this change, when dealing just with points on a single plate, a different reference frame can be used, whose coordinates are fixed to a particular plate, such as NAD83 for North America or ETRS89 for Europe.

Length of a degree of longitude

The length of a degree of longitude depends only on the radius of a circle of latitude. For a sphere of radius a that radius at latitude φ is (cos φ) times a, and the length of a one-degree (or π/180 radians) arc along a circle of latitude is

$$\Delta^1_{\mathrm{LONG}} = \frac{\pi}{180} a \cos\phi$$

ϕ	Δ^1_{LAT}	Δ^1_{LONG}
0°	110.574 km	111.320 km
15°	110.649 km	107.551 km
30°	110.852 km	96.486 km
45°	111.132 km	78.847 km
60°	111.412 km	55.800 km
75°	111.618 km	28.902 km
90°	111.694 km	0.000 km

When the Earth is modelled by an ellipsoid this arc length becomes [7][8]

$$\Delta^1_{\mathrm{LONG}} = \frac{\pi a \cos\phi}{180(1 - e^2 \sin^2\phi)^{1/2}}$$

where *e*, the eccentricity of the ellipsoid, is related to the major and minor axes (the equatorial and polar radii respectively) by

$$e^2 = \frac{a^2 - b^2}{a^2}$$

An alternative formula is

$$\Delta^1_{\mathrm{LONG}} = \frac{\pi}{180} a \cos\psi$$

where $\tan\psi = \frac{b}{a}\tan\phi$

Cos φ decreases from 1 at the equator to zero at the poles, so the length of a degree of longitude decreases likewise. This contrasts with the small (1%) increase in the length of a degree of latitude, equator to pole. The table shows both for the WGS84 ellipsoid with *a* = 6,378,137.0 m and *b* = 6,356,752.3142 m. Note that the distance between two points 1 degree apart on the same circle of latitude, measured along that circle of latitude, is slightly more than the shortest (geodesic) distance between those points; the difference is less than 0.6 m.

Ecliptic latitude and longitude

Ecliptic latitude and longitude are defined for the planets, stars, and other celestial bodies in a broadly similar way to that in which terrestrial latitude and longitude are defined, but there is a special difference.

The plane of zero latitude for celestial objects is the plane of the ecliptic. This plane is not parallel to the plane of the celestial equator, but rather is inclined to it by the *obliquity of the ecliptic*, which currently has a value of about 23° 26′. The closest celestial counterpart to terrestrial latitude is declination, and the closest celestial counterpart to terrestrial longitude is right ascension. These celestial coordinates bear the same relationship to the celestial equator as terrestrial latitude and longitude do to the terrestrial equator, and they are also more frequently used in astronomy than celestial longitude and latitude.

The polar axis (relative to the celestial equator) is perpendicular to the plane of the Equator, and parallel to the terrestrial polar axis. But the (north) pole of the ecliptic, relevant to the definition of ecliptic latitude, is the normal to the ecliptic plane nearest to the direction of the celestial north pole of the Equator, i.e. 23° 26′ away from it.

Ecliptic latitude is measured from 0° to 90° north (+) or south (−) of the ecliptic. Ecliptic longitude is measured from 0° to 360° eastward (the direction that the Sun appears to move relative to the stars), along the ecliptic from the vernal equinox. The equinox at a specific date and time is a fixed equinox, such as that in the J2000 reference frame.

However, the equinox moves because it is the intersection of two planes, both of which move. The ecliptic is relatively stationary, wobbling within a 4° diameter circle relative to the fixed stars over millions of years under the

gravitational influence of the other planets. The greatest movement is a relatively rapid gyration of Earth's equatorial plane whose pole traces a 47° diameter circle caused by the Moon. This causes the equinox to precess westward along the ecliptic about 50″ per year. This moving equinox is called the *equinox of date*. Ecliptic longitude relative to a moving equinox is used whenever the positions of the Sun, Moon, planets, or stars at dates other than that of a fixed equinox is important, as in calendars, astrology, or celestial mechanics. The 'error' of the Julian or Gregorian calendar is always relative to a moving equinox. The years, months, and days of the Chinese calendar all depend on the ecliptic longitudes *of date* of the Sun and Moon. The 30° zodiacal segments used in astrology are also relative to a moving equinox. Celestial mechanics (here restricted to the motion of solar system bodies) uses both a fixed and moving equinox. Sometimes in the study of Milankovitch cycles, the invariable plane of the solar system is substituted for the moving ecliptic. Longitude may be denominated from 0 to 2π radians in either case.

Longitude on bodies other than Earth

Planetary co-ordinate systems are defined relative to their mean axis of rotation and various definitions of longitude depending on the body. The longitude systems of most of those bodies with observable rigid surfaces have been defined by references to a surface feature such as a crater. The north pole is that pole of rotation that lies on the north side of the invariable plane of the solar system (near the ecliptic). The location of the Prime Meridian as well as the position of body's north pole on the celestial sphere may vary with time due to precession of the axis of rotation of the planet (or satellite). If the position angle of the body's Prime Meridian increases with time, the body has a direct (or prograde) rotation; otherwise the rotation is said to be retrograde.

In the absence of other information, the axis of rotation is assumed to be normal to the mean orbital plane; Mercury and most of the satellites are in this category. For many of the satellites, it is assumed that the rotation rate is equal to the mean orbital period. In the case of the giant planets, since their surface features are constantly changing and moving at various rates, the rotation of their magnetic fields is used as a reference instead. In the case of the Sun, even this criterion fails (because its magnetosphere is very complex and does not really rotate in a steady fashion), and an agreed-upon value for the rotation of its equator is used instead.

For *planetographic longitude*, west longitudes (i.e., longitudes measured positively to the west) are used when the rotation is prograde, and east longitudes (i.e., longitudes measured positively to the east) when the rotation is retrograde. In simpler terms, imagine a distant, non-orbiting observer viewing a planet as it rotates. Also suppose that this observer is within the plane of the planet's equator. A point on the Equator that passes directly in front of this observer later in time has a higher planetographic longitude than a point that did so earlier in time.

However, *planetocentric longitude* is always measured positively to the east, regardless of which way the planet rotates. *East* is defined as the counter-clockwise direction around the planet, as seen from above its north pole, and the north pole is whichever pole more closely aligns with the Earth's north pole. Longitudes traditionally have been written using "E" or "W" instead of "+" or "−" to indicate this polarity. For example, the following all mean the same thing:

- −91°
- 91°W
- +269°
- 269°E.

The reference surfaces for some planets (such as Earth and Mars) are ellipsoids of revolution for which the equatorial radius is larger than the polar radius; in other words, they are oblate spheroids. Smaller bodies (Io, Mimas, etc.) tend to be better approximated by triaxial ellipsoids; however, triaxial ellipsoids would render many computations more complicated, especially those related to map projections. Many projections would lose their elegant and popular properties. For this reason spherical reference surfaces are frequently used in mapping programs.

The modern standard for maps of Mars (since about 2002) is to use planetocentric coordinates. The meridian of Mars is located at Airy-0 crater.[9]

Tidally-locked bodies have a natural reference longitude passing through the point nearest to their parent body: 0° the center of the primary-facing hemisphere, 90° the center of the leading hemisphere, 180° the center of the anti-primary hemisphere, and 270° the center of the trailing hemisphere.[10] However, libration due to non-circular orbits or axial tilts causes this point to move around any fixed point on the celestial body like an analemma.

References

[1] Oxford English Dictionary

[2] Vespucci, Amerigo. "Letter from Seville to Lorenzo di Pier Francesco de' Medici, 1500." Pohl, Frederick J. **Amerigo Vespucci: Pilot Major**. New York: Columbia University Press, 1945. 76-90. Page 80.

[3] " Longitude clock comes alive (http://news.bbc.co.uk/2/hi/science/nature/1864737.stm)". BBC. March 11, 2002.

[4] Coordinate Conversion (http://www.colorado.edu/geography/gcraft/notes/datum/gif/llhxyz.gif)

[5] "λ = Longitude east of Greenwich (for longitude west of Greenwich, use a minus sign)." John P. Snyder, *Map Projections, A Working Manual* (http://pubs.er.usgs.gov/usgspubs/pp/pp1395), USGS Professional Paper 1395, page ix

[7] Osborne, P (2008) The Mercator Projections (http://mercator.myzen.co.uk/mercator.pdf)(Chapter 5)

[8] Rapp, Richard H. (1991). *Geometric Geodesy, Part I*, Dept. of Geodetic Science and Surveying, Ohio State Univ., Columbus, Ohio. (http://hdl.handle.net/1811/24333)(Chapter 3)

[9] Where is zero degrees longitude on Mars? (http://www.esa.int/SPECIALS/Mars_Express/SEM0VQV4QWD_0.html) - Copyright 2000 - 2010 © European Space Agency. All rights reserved.

[10] First map of extraterrestrial planet (http://www.cfa.harvard.edu/image_archive/2007/31/lores.jpg) - Center of Astrophysics.

External links

- Resources for determining your latitude and longitude (http://jan.ucc.nau.edu/~cvm/latlon_find_location.html)
- IAU/IAG Working Group On Cartographic Coordinates and Rotational Elements of the Planets and Satellites (http://www.hnsky.org/iau-iag.htm)
- "Longitude forged" (http://entertainment.timesonline.co.uk/tol/arts_and_entertainment/the_tls/article5136819.ece): an essay exposing a hoax solution to the problem of calculating longitude, undetected in Dava Sobel's Longitude, from TLS (http://www.the-tls.co.uk), November 12, 2008.
- Longitude And Latitude Of Points of Interest (http://www.thegpscoordinates.com)
- Length Of A Degree Of Latitude And Longitude Calculator (http://www.csgnetwork.com/degreelenllavcalc.html)

History of longitude

The **history of longitude** is a record of the effort, by navigators and scientists over several centuries, to discover a means of determining longitude.

The measurement of longitude is important to both cartography and navigation. Historically, the most important practical application of these was to provide safe ocean navigation. Knowledge of both latitude and longitude was required. Finding a method of determining longitude took centuries and involved some of the greatest scientific minds.

Monuments of International Longitude Determination at Sheshan Observatory, Shanghai

Ancient history

Eratosthenes in the 3rd century BC first proposed a system of latitude and longitude for a map of the world. By the 2nd century BC Hipparchus was the first to use such a system to uniquely specify places on the earth. He also proposed a system of determining longitude by comparing the local time of a place with an absolute time. This is the first recognition that longitude can be determined by accurate knowledge of time. In the 11th century Al-Biruni believed the earth rotated on its axis and this forms our modern notion of how time and longitude are related.[1]

Problem of longitude

Determining longitude on land was fairly easy compared to the task at sea. A stable surface to work from, a comfortable location to live in while performing the work and the ability to repeat determinations over time made for great accuracy. Whatever could be discovered from solving the problem at sea would only improve the determination of longitude on land.

Determining latitude was relatively easy in that it could be found from the altitude of the sun at noon with the aid of a table giving the sun's declination for the day.[2] For longitude, early ocean navigators had to rely on dead reckoning. This was inaccurate on long voyages out of sight of land and these voyages sometimes ended in tragedy as a result.

In order to avoid problems with not knowing one's position accurately, navigators have, where possible, relied on taking advantage of their knowledge of latitude. They would sail to the latitude of their destination, turn toward their destination and follow a line of constant latitude. This was known as *running down a westing* (if westbound, easting otherwise).[3] This prevented a ship from taking the most direct route (a great circle) or a route with the most favourable winds and currents, extending the voyage by days or even weeks. This increased the likelihood of short rations,[4] which could lead to poor health or even death for members of the crew due to scurvy or starvation, with resultant risk to the ship.

Errors in navigation have also resulted in shipwrecks. Motivated by a number of maritime disasters attributable to serious errors in reckoning position at sea, particularly such spectacular disasters as the Scilly naval disaster of 1707, which took Admiral Sir Cloudesley Shovell and his fleet, the British government established the Board of Longitude in 1714:

> "The Discovery of the Longitude is of such Consequence to Great Britain for the safety of the Navy and Merchant Ships as well as for the improvement of Trade that for want thereof many Ships have been retarded in their voyages, and many lost..." [and there will be a Longitude Prize] "for such person or persons as shall discover the Longitude."

The prizes were to be awarded for the discovery and demonstration of a practical method for determining the longitude of a ship at sea. Prizes were offered in graduated amounts for solutions of increasing accuracy. These prizes, worth the equivalent of millions of dollars in today's currency, motivated many to search for a solution.

Britain was not alone in the desire to solve the problem. France's King Louis XIV founded the Académie Royale des Sciences in 1666. It was charged with, among a range of other scientific activities, advancement of the science of navigation and the improvement of maps and sailing charts. From 1715, the Académie offered one of the two *Prix Rouillés* specifically for navigation.[5] Spain's Philip II offered a prize for the discovery of a solution to the problem of the longitude in 1567; Philip III increased the prize in 1598. Holland added to the effort with a prize offered in 1636.[1] Navigators and scientists in most European countries were aware of the problem and were involved in finding a solution. Due to the international effort in solving the problem and the scale of the enterprise, it represented one of the largest scientific endeavours in history.

Time equals longitude

Since the Earth rotates at a steady rate of 360° per day, or 15° per hour (in mean solar time), there is a direct relationship between time and longitude. If the navigator knew the time at a fixed reference point when some event occurred at the ship's location, the difference between the reference time and the apparent local time would give the ship's position relative to the fixed location. Finding apparent local time is relatively easy. The problem, ultimately, was how to determine the time at a distant reference point while on a ship.

Proposed methods of determining time

The first publication of a method of determining time by observing the position of the Earth's moon was by Johannes Werner in his "In hoc opere haec continentur Nova translatio primi libri geographiae Cl. Ptolomaei", published at Nürnberg in 1514. The method was discussed in detail by Petrus Apianus in his Cosmographicus liber (Landshut 1524).

It appears that Johannes Werner inspired by Amerigo Vespucci's letter written in 1502 where he wrote: ". . . I maintain that I learned [my longitude] . . . by the eclipses and conjunctions of the Moon with the planets; and I have lost many nights of sleep in reconciling my calculations with the precepts of those sages who have devised the manuals and written of the movements, conjunctions, aspects, and eclipses of the two luminaries and of the wandering stars, such as the wise King Don Alfonso in his Tables, Johannes Regiomontanus in his Almanac, and Blanchinus, and the Rabbi Zacuto in his almanac, which is perpetual; and these were composed in different meridians: King Don Alfonso's book in the meridian of Toledo, and Johannes Regiomontanus's in that of Ferrara, and the other two in that of Salamanca."2 The best "clock" to use for reference, is the stars. In the roughly 27.3 solar days of a lunar orbit, the Moon moves a full 360 degrees around the sky, returning to its old position among the stars. This is 13 degrees per day, or just over 0.5 degree per hour. So, while the rotation of the Earth causes the stars and the Moon to appear to move from east to west across the night sky, the Moon, because of its own orbit around the Earth, fights back against this apparent motion, and seems to move eastward (or retrograde) by about 0.5 degree per hour. In other words, the Moon "moves" west only 11.5 degrees per hour."

Galileo's proposal — Jovian moons

In 1612, having determined the orbital periods of Jupiter's four brightest satellites (Io, Europa, Ganymede and Callisto), Galileo proposed that with sufficiently accurate knowledge of their orbits one could use their positions as a universal clock, which would make possible the determination of longitude. He worked on this problem from time to time during the remainder of his life.

To be successful, this method required the observation of the moons from the deck of a moving ship. To this end, Galileo proposed the celatone, a device in the form of a helmet with a telescope mounted so as to accommodate the motion of the observer on the ship.[6] This was later replaced with the idea of a pair of nested hemispheric shells separated by a bath of oil. This would provide a platform that would allow the observer to remain stationary as the ship rolled beneath him, in the manner of a gimballed platform. To provide for the determination of time from the observed moons' positions, a Jovilabe was offered — this was an analogue computer that calculated time from the positions and that got its name from its similarities to an astrolabe.[7] The practical problems were severe and the method was never used at sea. However, it was used for longitude determination on land.

Halley's proposals — lunar occultations and appulses, magnetic deviation

Around 1683, Edmund Halley proposed using a telescope to observe the time of occultations or appulses of a star by the moon as a means of determining time while at sea.[8] He had accumulated observations of the moon's position and of certain stars to this end, and had deduced the means of correcting errors in predictions of the moon's position.

Upon succeeding John Flamsteed in the post of Astronomer Royal, Halley had undertaken the task of observing both stellar positions and the path of the moon, with the intention of supplementing existing knowledge and advancing his proposal for determining longitude at sea.[8] By this time, he had abandoned the use of occultations in preference for appulses exclusively. No reason was given by Halley for abandoning occultations, however, there are few bright stars occulted by the moon and the task of documenting the dim stars' positions and training navigators to recognize them would be daunting. Appulses with brighter stars would be more practical.

While he had tested the method at sea, it was never widely used or considered as a viable method. His observations did contribute to the lunar distance method.

Halley also hoped that careful observations of magnetic deviations could provide a determination of longitude. The magnetic field of the Earth was not well understood at the time. Mariners had observed that magnetic north deviated from geographic north in many locations. Halley and others hoped that the pattern of deviation, if consistent, could be used to determine longitude. If the measured deviation matched that recorded on a chart, the position would be known. Halley used his voyages on the pink *Paramour* to study the magnetic variance and was able to provide maps showing the *halleyan* or *isogonic* lines. This method was eventually to fail as the localized variations from general magnetic trends make the method unreliable.

Maskelyne's proposal — lunar distance method

The first publication of a method of determining time by observing the position of the Earth's moon was by Johannes Werner in his *In hoc opere haec continentur Nova translatio primi libri geographiae Cl. Ptolomaei*, published at Nürnberg in 1514. The method was discussed in detail by Petrus Apianus in his *Cosmographicus liber* (Landshut 1524).

A Frenchman, the Sieur de St. Pierre, brought the technique to the attention of King Charles II of England in 1674.[9] Being enthusiastic for the proposed technique, the king contacted his royal commissioners, who included Robert Hooke. They in turn consulted the astronomer John Flamsteed. Flamsteed supported the feasibility of the method but lamented the lack of detailed knowledge of the stellar positions and the moon's movement. King Charles responded by accepting Flamsteed's suggestion of the establishment of an observatory and appointed Flamsteed as the first Astronomer Royal. With the creation of the Royal Observatory, Greenwich and a program for measuring the

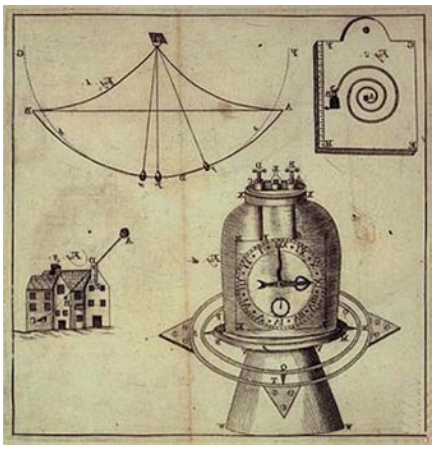
positions of the stars with high precision, the process of developing a working method of lunar distances was under way.[10] To further the astronomers' ability to predict the moon's motion, Isaac Newton's theory of gravitation could be applied to the motion of the moon.

Tobias Mayer, the German astronomer, had been working on the lunar distance method in order to determine accurately positions on land. He had corresponded with Leonhard Euler, who contributed information and equations to describe the motions of the moon.[11] With these studies, Mayer had produced a set of tables predicting the position of the Moon more accurately than ever before. These were sent to the Board of Longitude for evaluation and consideration for the Longitude Prize. With these tables and after his own experiments at sea trying out the lunar distance method, Nevil Maskelyne proposed annual publication of lunar distance predictions in an official nautical almanac for the purpose of finding longitude at sea to within half a degree.

Being very enthusiastic for the lunar distance method, Maskelyne and his team of human computers worked feverishly through the year 1766, preparing tables for the new Nautical Almanac and Astronomical Ephemeris. Published first with data for the year 1767, it included daily tables of the positions of the Sun, Moon, and planets and other astronomical data, as well as tables of lunar distances giving the distance of the Moon from the Sun and nine stars suitable for lunar observations (ten stars for the first few years).[12] [13] This publication later became the standard almanac for mariners worldwide, and since it was based on the Royal Observatory, it led to the international adoption of Greenwich Mean Time as an international standard.

Harrison's proposal — marine chronometer

Another proposed solution was to use a mechanical timepiece, to be carried on a ship, that would maintain the correct time at a reference location. The concept of using a clock can be attributed to Gemma Frisius. Attempts had been made on land using pendulum clocks, with some success. In particular, Huygens had made accurate pendulum clocks that made it possible to determine longitude on land. He also proposed the use of a balance spring to regulate clocks. There is some dispute as to whether he or Robert Hooke first proposed this idea.[14] However, many, including Isaac Newton, were pessimistic that a clock of the required accuracy could ever be developed. At that time, there were no clocks that could maintain accurate time while being subjected to the conditions of a moving ship. The rolling, pitching and yawing, coupled with the pounding of wind and waves, would knock existing clocks out of the correct time.



Chronometer of Jeremy Thacker.

In spite of this pessimism, a group felt that the answer lay in chronometry -- developing an improved time piece that would work even on extended voyages at sea. A suitable timepiece was eventually built by John Harrison, a Yorkshire carpenter, with his marine chronometer; that timepiece was later known as *H-4.*

Harrison built five, two of which were tested at sea. His first, *H-1,* was not tested under the conditions that were required by the Board of Longitude. Instead, the Admiralty required that it travel to Lisbon and back. It performed excellently, but the perfectionist in Harrison prevented him from sending it on the required trial to the West Indies. He instead embarked on the construction of *H-2.* This chronometer never went to sea, and was immediately followed by *H-3.* Still not satisfied with his own work, Harrison produced *H-4,* which did get its sea trial and satisfied all the requirements for the Longitude Prize. However, he was not awarded the prize and was forced to fight for his reward.

Though the British Parliament rewarded John Harrison for his marine chronometer in 1773, his chronometers were not to become standard. Chronometers such as those by Thomas Earnshaw were suitable for general nautical use by the end of the 18th century. However, they remained very expensive and the lunar distance method continued to be

used for some decades.

Lunars or chronometers?

The lunar distance method was initially labour intensive because of the time-consuming complexity of the calculations for the Moon's position. Early trials of the method could involve four hours of effort.[10] However, the publication of the Nautical Almanac starting in 1767 provided tables of pre-calculated distances of the Moon from various celestial objects at three-hour intervals for every day of the year, making the process practical by reducing the time for calculations to less than 30 minutes and as little as ten minutes with some efficient tabular methods.[15] Lunar distances were widely used at sea from 1767 to about 1850.

Between 1800 and 1850 (earlier in British and French navigation practice, later in American, Russian, and other maritime countries), affordable, reliable marine chronometers became available, replacing the method of lunars as soon as they reached the market in large numbers. It became possible to buy two or more relatively inexpensive chronometers, serving as checks on each other, rather than acquiring a single (and expensive) sextant of sufficient quality for lunar distance navigation.[]

By 1850, the vast majority of ocean-going navigators worldwide had ceased using the method of lunar distances. Nonetheless, expert navigators continued to learn lunars as late as 1905, though for most this was a textbook exercise since they were a requirement for certain licenses. They also continued in use in land exploration and mapping where chronometers could not be kept secure in harsh conditions. The British Nautical Almanac published lunar distance tables until 1906 and the instructions until 1924.[16] Such tables last appeared in the 1912 USNO Nautical Almanac, though an appendix explaining how to generate single values of lunar distances was published as late as the early 1930s.[13] The presence of lunar distance tables in these publications until the early 20th century does not imply common usage until that time period but was simply a necessity due to a few remaining (soon to be obsolete) licensing requirements. The development of wireless telegraph time signals in the early 20th century, used in combination with marine chronometers, put a final end to the use of lunar distance tables.

Modern solutions

Time signals were first broadcast by wireless telegraphy in 1904, by the US Navy from Navy Yard in Boston. Another regular broadcast began in Halifax, Nova Scotia in 1907, and time signals that became more widely used were broadcast from the Eiffel Tower starting in 1910.[17] As ships adopted radio telegraph sets for communication, such time signals were used to correct chronometers. This method drastically reduced the importance of lunars as a means of verifying chronometers.

Modern sailors have a number of choices for determining accurate positional information, including radar and the Global Positioning System, commonly known as GPS, a satellite navigation system. With technical refinements that make position fixes accurate to within meters, the radio-based LORAN system was used in the late 20th Century but has been discontinued in North America. Combining independent methods is used as a way to improve the accuracy of position fixes. Even with the availability of multiple modern methods of determining longitude, a marine chronometer and sextant are routinely carried as a backup system.

Further refinements for longitude on land

For the determination of longitude on land, the preferred method became exchanges of chronometers between observatories to accurately determine the differences in local times in conjunction with observation of the transit of stars across the meridian.

An alternative method was the simultaneous observation of occultations of stars at different observatories. Since the event occurred at a known time, it provided an accurate means of determining longitude. In some cases, special expeditions were mounted to observe a special occultation or eclipse to determine the longitude of a location without a permanent observatory.

From the mid-19th century, telegraph signalling allowed more precisely synchronization of star observations. This significantly improved longitude measurement accuracy. The Royal Observatory in Greenwich and the U.S. Coast Survey coordinated European and North American longitude measurement campaigns in the 1850s and 1860s, resulting in improved map accuracy and navigation safety. Synchronization by radio followed in the early 20th century. In the 1970s, the use of satellites was developed to more precisely measure geographic coordinates (GPS).

Notable scientific contributions

In the process of searching for a solution to the problem of determining longitude, many scientists added to the knowledge of astronomy and physics.

- Galileo - detailed studies of Jupiter's moons, which proved Ptolemy's assertion that not all celestial objects orbit the Earth
- Robert Hooke - determination of the relationship between forces and displacements in springs, laying the foundations for the theory of elasticity.
- Christiaan Huygens - invention of pendulum clock and a spring balance for pocket watch.
- Jacob Bernoulli, with refinements by Leonhard Euler - invention of the calculus of variations for Bernoulli's solution of the brachistochrone problem (finding the shape of the path of a pendulum with a period that does not vary with degree of lateral displacement). This refinement created greater accuracy in pendulum clocks.
- John Flamsteed and many others - formalization of observational astronomy by means of astronomical observatory facilities, further advancing modern astronomy as a science.
- John Harrison - invention of the gridiron pendulum and bimetallic strip along with further studies in the thermal behavior of materials. This contributed to the evolving science of Solid mechanics. Invention of caged roller bearings contributed to refinements in mechanical engineering designs.

References

[1] Longitude and the Académie Royale (http://www-groups.dcs.st-and.ac.uk/~history/PrintHT/Longitude1.html)

[2] Latitude can also be determined from Polaris, the northern pole star. However, since Polaris is not precisely at the pole, it can only estimate the latitude unless the precise time is known or many measurements are made over time. While many measurements can be made on land, this makes it impractical for determining latitude at sea.

[3] *Dutton's Navigation and Piloting*, 12th edition. G.D. Dunlap and H.H. Shufeldt, eds. Naval Institute Press 1972, ISBN 0-87021-163-3

[4] As food stores ran low, the crew would be put on rations to extend the time with food This was referred to as giving the crew *short rations, short allowance* or *petty warrant*.

[5] Taylor, E.G.R., *The Haven-finding Art: A History of Navigation from Odysseus to Captain Cook,* Hollis & Carter, London 1971, ISBN 0-370-01347-6

[6] Celatone (http://brunelleschi.imss.fi.it/museum/esim.asp?c=500174)

[7] Jovilabe (http://brunelleschi.imss.fi.it/museum/esim.asp?c=404003)

[8] Halley, Edmund, *A Proposal of a Method for Finding the Longitude at Sea Within a Degree, or Twenty Leagues.*, Philosophical Transactions of the Royal Society, Vol. 37, 1731-1732, pp 185-195

[9] Forbes, Eric G., " The origins of the Greenwich observatory (http://adsabs.harvard.edu/abs/1977VA.....20...39F)", *Vistas in Astronomy*, vol. 20, Issue 1, pp.39-50

[10] Sobel, Dava, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*, Walker and Company, New York, 1995 ISBN 0-8027-1312-2

[11] Landes, David S., *Revolution in Time*, Belknap Press of Harvard University Press, Cambridge Mass., 1983, ISBN 0-674-76800-0
[14] "The Man Who Knew Too Much", The Strange and Inventive Life of Robert Hooke, Stephen Inwood, Pan Books 2003 ISBN 03300488295
[15] *The Nautical Almanac and Astronomical Ephemeris, for the year 1767*, London: W. Richardson and S. Clark, 1766
[16] The Nautical Almanac Abridged for the Use of Seamen, 1924
[17] Lombardi, Michael A., , *Proceedings of the 2003 National Conference of Standards Laboratories International*, August 17, 2003

External links

- The NavList community: devoted to the history, preservation, and practice of traditional navigation techniques (http://www.fer3.com/NavList/)
- PBS Nova Online: *Lost at Sea, the Search for Longitude* (http://www.pbs.org/wgbh/nova/longitude/)

Reflecting instrument

Reflecting instruments are those that use mirrors to enhance their ability to make measurements. In particular, the use of mirrors permits one to observe two objects simultaneously while measuring the angular distance between the objects. While they are used in many professions, they are primarily associated with celestial navigation, as the need to solve navigation problems, in particular the problem of the longitude, was the primary motivation in their development.

Objectives of the instruments

The purpose of reflecting instruments as to allow an observer to measure the altitude of a celestial object or measure the angular distance between two objects. The driving force behind the developments discussed here was the solution to the problem of finding one's longitude at sea. The solution to this problem was seen to require an accurate means of measuring angles and the accuracy was seen to rely on the observer's ability to measure this angle by simultaneously observing two objects at once.

The deficiency of prior instruments was well known. By requiring the observer to observe two objects with two divergent lines of sight increased the likelihood of an error. Those that considered the problem realized that the use of specula (mirrors in modern parlance) could permit two objects to be observed in a single view. What followed is a series of inventions and improvements that refined the instrument to the point that its accuracy exceeded that which was required for determining longitude. Any further improvements required a completely new technology.

Early reflecting instruments

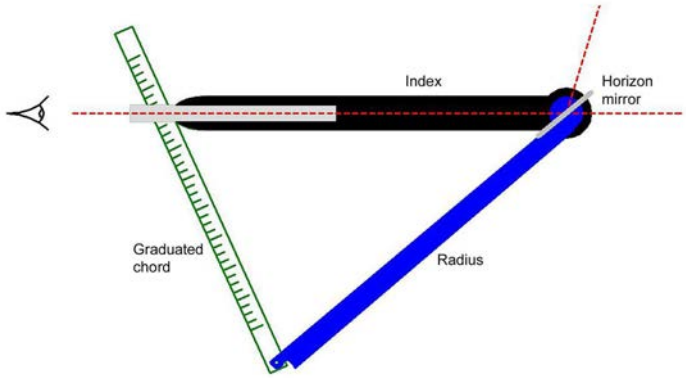
Some of the early reflecting instruments were proposed by scientists such as Robert Hooke and Isaac Newton. These were little used or may not have been built or tested extensively. The van Breen instrument was the exception, in that it was used by the Dutch. However, it had little influence outside of the Netherlands.

Joost van Breen's reflecting cross-staff

Invented in 1660 by the Dutch Joost van Breen, the **spiegelboog** (mirror-bow) was a reflecting cross staff. This instrument appears to have been used for approximately 100 years, mainly in the Zeeland Chamber of the VOC (The Dutch East India Company).[1]

Robert Hooke's Single-reflecting instrument

Hooke's instrument was a single-reflecting instrument. It used a single mirror to reflect the image of an astronomical object to the observer's eye.[2] This instrument was first described in 1666 and a working model was presented by Hooke at a meeting of the Royal Society some time later.



Representative drawing of Hooke's reflecting instrument. It does not accurately depict the fine details of the instrument but rather the basic functionality.The index with telescope mounted is shown in black, the radius arm with the mirror (grey) attached in blue and the chord in green on white. The lines of sight are represented by the red dashed line.

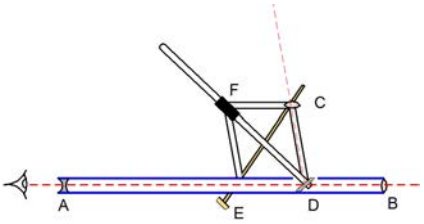
The device consisted of three primary components, an index arm, a radial arm and a graduated chord. The three were arranged in a triangle as in the image on the right. A telescopic sight was mounted on the index arm. At the point of rotation of the radial arm, a single mirror was mounted. This point of rotation allowed the angle between the index arm and the radial arm to be changed. The graduated chord was connected to the opposite end of the radial arm and the chord was permitted to rotate about the end. The chord was held against the distant end of the index arm and slid against it. The graduations on the chord were uniform and, by using it to measure the distance between the ends of the index arm and the radial arm, the angle between those arms could be determined. A table of chords was used to convert a measurement of distance to a measurement of angle. The use of the mirror resulted in the measured angle being twice the angle included by the index and the radius arm.

The mirror on the radial arm was small enough that the observer could see the reflection of an object in half the telescope's view while seeing straight ahead in the other half. This allowed the observer to see both objects at once. Aligning the two objects together in the telescopes view resulted in the angular distance between them to be represented on the graduated chord.

While Hooke's instrument was novel and attracted some attention at the time, there is no evidence that it was subjected to any tests at sea.[2] The instrument was little used and did not have any significant effect on astronomy or navigation.

Halley's reflecting instrument

In 1692, Edmond Halley presented the design of a reflecting instrument to the Royal Society.[2]



A drawing of Halley's reflecting instrument. The telescope is represented by the blue lines (as if cut open) and the mirrors and lenses are grey. The red dashed lines represent lines of sight.

This is an interesting instrument, combining the functionality of a radio latino with a double telescope. The telescope (AB in the image to the right), has an eyepiece at one end and a mirror (D) partway along its length with one objective lens at the far end (B). The mirror only obstructs half the field (either left or right) and permits the objective to be seen on the other. Reflected in the mirror is the image from the second objective lens (C). This permits the observer to see both images, one straight through and one reflected, simultaneously besides each other. It is essential that the focal lengths of the two objective lenses be the same and that the distances from the mirror to either lens be identical. If this condition is not met, the two images cannot be brought to a common focus.

The mirror is mounted on the staff (DF) of the radio latino portion of the instrument and rotates with it. The angle this side of the radio latino's rhombus makes to the telescope can be set by adjusting the rhombus' diagonal length. In order to facilitate this and allow for fine adjustment of the angle, a screw (EC) is mounted so as to allow the observer to change the distance between the two vertexes (E and C).

The observer sights the horizon with the direct lens' view and sights a celestial object in the mirror. Turning the screw to bring the two images directly adjacent sets the instrument. The angle is determined by taking the length of the screw between E and C and converting this to an angle in a table of chords.

Halley specified that the telescope tube be rectangular in cross section. This makes construction easy, but is not a requirement as other cross section shapes can be accommodated. The four sides of the radio latino portion (CD, DE, EF, FC) must be equal in length in order for the angle between the telescope and the objective lens side (AD-DC) to be precisely twice the angle between the telescope and the mirror (AD-DF) (or in other words - to enforce the angle of incidence being equal to the angle of reflection). Otherwise, instrument collimation will be compromised and the resulting measurements would be in error.

The celestial object's elevation angle could have been determined by reading from graduations on the staff at the slider, however, that's not how Halley designed the instrument. This may suggest that the overall design of the instrument was coincidentally like a radio latino and that Halley may not have been familiar with that instrument.

There is no knowledge of whether this instrument was ever tested at sea.[2]

Newton's reflecting quadrant

Newton's reflecting quadrant was similar in many respects to Hadley's first reflecting quadrant that followed it.

Newton had communicated the design to Edmund Halley around 1699. However, Halley did not do anything with the document and it remained in his papers only to be discovered after his death.[3] However, Halley did discuss Newton's design with members of the Royal Society when Hadley presented his reflecting quadrant in 1731. Halley noted that Hadley's design was quite similar to the earlier Newtonian instrument.[2]

As a result of this inadvertent secrecy, Newton's invention played little role in the development of reflecting instruments.

The octant

What is remarkable about the octant is the number of persons who independently invented the device in a short period of time. John Hadley and Thomas Godfrey both get credit for inventing the octant. They independently developed the same instrument around 1731. They were not the only ones, however.

In Hadley's case, two instruments were designed. The first was an instrument very similar to Newton's reflecting quadrant. The second had essentially the same form as the modern sextant. Few of the first design were constructed, while the second became the standard instrument from which the sextant derived and, along with the sextant, displaced all prior navigation instruments used for celestial navigation.

Caleb Smith, an English insurance broker with a strong interest in astronomy, had created an octant in 1734. He called it an *Astroscope* or *Sea-Quadrant*.[4] He used a fixed prism in addition to an index mirror to provide reflective elements. Prisms provide advantages over mirrors in an era when polished speculum metal mirrors were inferior and both the silvering of a mirror and the production of glass with flat, parallel surfaces was difficult. However, the other design elements of Smith's instrument made it inferior to Hadley's octant and it was not used significantly.[3]

Jean-Paul Fouchy, a mathematics professor and astronomer in France invented an octant in 1732.[3] His was essentially the same as Hadley's. Fouchy did not know of the developments in England at the time, since communications between the two country's instrument makers was limited and the publications of the Royal Society, particularly the *Philosophical Transactions*, were not being distributed in France.[5] Fouchy's octant was overshadowed by Hadley's.

The sextant

The main article, Sextant, covers the use of the instrument in navigation. This article concentrates on the history and the development of the instrument

The origin of the sextant is straightforward and not in dispute. Admiral John Campbell, having used Hadley's octant in sea trials of the method of lunar distances, found that it was wanting. The 90° angle subtended by the arc of the instrument was insufficient to measure some of the angular distances required for the method. He suggested that the angle be increased to 120°, yielding the sextant. John Bird made the first such sextant in 1757.[6]

A sextant that has been used for over a half century. This frame shows one standard design - that with three rings. This is one design that has been used to avoid thermal expansion problems while retaining adequate stiffness.

With the development of the sextant, the octant became something of a second class instrument. The octant, while occasionally constructed entirely of brass, remained primarily a wooden-framed instrument. Most of the developments in advanced materials and construction techniques were reserved for the sextant.

There are examples of sextants made with wood, however most are made from brass. In order to ensure the frame was stiff, instrument makers used thicker frames. This had a drawback in making the instrument heavier, which could influence the accuracy due to hand-shaking as the navigator worked against its weight. In order to avoid this problem, the frames were modified. Edward Troughton patented the double-framed sextant in 1788.[7] This used two frames held in parallel with spacers. The two frames were about a centimetre apart. This significantly increased the stiffness of the frame. An earlier version had a second frame that only covered the upper part of the instrument, securing the mirrors and telescope. Later versions used two full frames. Since the spacers looked like little pillars, these were also called *pillar sextants*.

Troughton also experimented with alternative materials. The scales were plated with silver, gold or platinum. Gold and platinum both minimized corrosion problems. The platinum-plated instruments were expensive, due to the scarcity of the metal, though less expensive than gold. Troughton knew William Hyde Wollaston through the Royal Society and this gave him access to the precious metal.[8] Instruments from Troughton's company that used platinum can be easily identified by the word *Platina* engraved on the frame. These instruments remain highly valued as collector's items and are as accurate today as when they were constructed.[9]

As the developments in dividing engines progressed, the sextant was more accurate and could be made smaller. In order to permit easy reading of the vernier, a small magnifying lens was added. In addition, to reduce glare on the frame, some had a diffuser surrounding the magnifier to soften the light. As accuracy increased, the circular arc vernier was replaced with a drum vernier.

Frame designs were modified over time to create a frame that would not be adversely affected by temperature changes. These frame patterns became standardized and one can see the same general shape in many instruments from many different manufacturers.

In order to control costs, modern sextants are now available in precision-made plastic. These are light, affordable and of high quality.

Types of sextants

While most people think of navigation when they hear the term *sextant*, the instrument has been used in other professions.

Navigator's sextant

: The common type of instrument most people think of when they hear the term *sextant*.

Sounding sextants

: These are sextants that were constructed for use horizontally rather than vertically and were developed for use in hydrographic surveys.[6]

Surveyor's sextants

: These were constructed for use exclusively on land for horizontal angular measurements. Instead of a handle on the frame, they had a socket to allow the attachment of a surveyor's Jacob's staff.

Box or pocket sextants

: These are small sextants entirely contained within a metal case. First developed by Edward Troughton, they are usually all brass with most of the mechanical components inside the case. The telescope extends from an opening in the side. The index and other parts are completely covered when the case cover is slipped on. Popular with surveyors for their small size (typically only 6.5–8 cm in diameter and 5 cm deep), their accuracy was enabled by improvements in the dividing engines used to graduate the arcs. The arcs are so small that magnifiers are attached to allow them to be read.[7]

In addition to these types, there are terms used for various sextants.

A *pillar sextant* can be either:

1. A double-frame sextant as patented by Edward Troughton in 1788.
2. A surveyor's sextant with a socket for a surveyor's staff (the pillar).[10]

The former is the most common use of the term.

Beyond the sextant

Quintant and others

Several makers offered instruments with sizes other than one-eighth or one-sixth of a circle. One of the most common was the *quintant* or fifth of a circle (72° arc reading to 144°). Other sizes were also available, but the odd sizes never became common. Many instruments are found with scales reading to, for example, 135°, but they are simply referred to as sextants. Similarly, there are 100° octants, but these are not separated as unique types of instruments.

There was interest in much larger instruments for special purposes. In particular a number of full circle instruments were made, categorized as reflecting circles and repeating circles.

Reflecting circles

The reflecting circle was invented by the German geometer and astronomer Tobias Mayer in 1752,[6] with details published in 1767.[3] His development preceded the sextant and was motivated by the need to create a superior surveying instrument.[3]

Borda's reflecting circle, on display at Toulon naval museum

The reflecting circle is a complete circular instrument graduated to 720° (To measure distances between heavenly bodies, there is no need to read an angle greater than 180°, since the minimum distance will always be less than 180°.). Mayer presented a detailed description of this instrument to the Board of Longitude and John Bird used the information to construct one sixteen inches in diameter for evaluation by the Royal Navy.[11] This instrument was one of those used by Admiral John Campbell during his evaluation of the lunar distance method. It differed in that it was graduated to 360° and was so heavy that it was fitted with a support that attached to a belt.[11] It was not considered better than the Hadley octant and was less convenient to use.[3] As a result, Campbell recommended the construction of the sextant.

Mendoça's reflecting circle on display at the Musée national de la Marine.

Jean-Charles de Borda further developed the reflecting circle. He modified the position of the telescopic sight in such a way that the mirror could be used to receive an image from either side relative to the telescope. This eliminated the need to ascertain that the mirrors were precisely parallel when reading zero. This simplified the use of the instrument. Further refinements were performed with the help of Etienne Lenoir. The two of them refined the instrument to its definitive form in 1777.[3] This instrument was so distinctive it was given the name *Borda circle*.[6]

Josef de Mendoza y Ríos redesigned Borda's reflecting circle (London, 1801). The goal was to use it together with his Lunar Tables published by the Royal Society (London, 1805). He made a design with two concentric circles and a vernier scale and recommended averaging three sequential readings to reduce the error. Borda's system was not based on a circle of 360° but 400 grads (Borda spent years calculating his tables with a circle divided in 400°). Mendoza's lunar tables have been used through almost the entire nineteenth century (see Lunar distance (navigation)).

Edward Troughton also modified the reflecting circle. He created a design with three index arms and verniers. This permitted three simultaneous readings to average out the error.

As a navigation instrument, the reflecting circle was more popular with the French navy than with the British.[6]

One instrument derived from the reflecting circle is the **repeating circle**. Invented by Lenoir in 1784,[3] Borda and Lenoir developed the instrument for geodetic surveying. Since it was not used for the celestial measures, it did not use double reflection and substituted two telescope sights. As such, it was not a reflecting instrument. It was notable as being the equal of the great theodolite created by the renowned instrument maker, Jesse Ramsden.

Bris Sextant

The **Bris sextant** is not a true sextant, but it is a true reflecting instrument based on the principle of double reflection and subject to the same rules and errors as common octants and sextants. Unlike common octants and sextants, the **Bris sextant** is a fixed angle instrument capable of accurately measuring a few specific angles unlike other reflecting instruments which can measure any angle within the range of the instrument. It is particularly suited to determining the altitude of the sun or moon.

References

[1] De Hilster, N., *The Spiegelboog (mirror-staff): a reconstruction*, Bulletin of the Scientific Instrument Society, No. 90, 2006 (http://www.dehilster.info/instrumenten/spiegelboog/sis_article_spiegelboog.pdf).

[2] Charles H. Cotter *The Mariner's Sextant and the Royal Society; Notes and Records of the Royal Society of London*, Vol. 33, No. 1 (Aug., 1978), pp. 23-36.

[3] Daumas, Maurice, *Scientific Instruments of the Seventeenth and Eighteenth Centuries and Their Makers*, Portman Books, London 1989 ISBN 978-0-7134-0727-3

[4] Bedini, Silvio, *History Corner: Benjamin King of Newport, R.I.-Part II*, Professional Surveyor Magazine, September 1997 Volume 17 Number 6 (http://www.profsurv.com/archive.php?issue=17&article=184)

[5] Fauque, Danielle, *Un instrument à réflexion pour la marine : deux propositions successives de Fouchy*, presented at Colloque Grandjean de Fouchy, March 23, 2007 at the Observatoire de Paris.

[6] Turner, Gerard L'E., *Nineteenth Century Scientific Instruments*, Sotheby Publications, 1983, ISBN 0-85667-170-3

[7] Turner, Gerard L'E., *Antique Scientific Instruments*, Blandford Press Ltd. 1980 ISBN 0-7137-1068-3

[8] Chaldecott, John A., *Platinum and Palladium in Astronomy and Navigation: The Pioneer Work of Edward Troughton and William Hyde Wollaston*, Platinum Metals Review, Volume 31 Issue 2 April 1987 Pages 91-100 Online version (pdf) (http://www.platinummetalsreview.com/pdf/pmr-v31-i2-091-100.pdf)

[9] Catalog 130, Spring 1987, Historical Technology Inc, Marblehead MA, USA

[10] *Tesseract - Early Scientific Instruments*, Volume Fifteen, Winter 1987. Catalogue entry for an "Adams Pillar Octant", a single frame octant used for surveying. It was made in London circa 1800. The photographs show the socket used for Jacob's staff.

[11] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1

External links

- National Maritime Museum (http://www.nmm.ac.uk/collections/explore/object.cfm?ID=BHC3130) Portrait of a merchant navy captain holding a Caleb Smith Octant.

Iceland spar

Iceland spar, formerly known as **Iceland crystal** (Icelandic: *silfurberg*; lit. *silver-rock*), is a transparent variety of calcite, or crystallized calcium carbonate, originally brought from Iceland, and used in demonstrating the polarization of light (see polarimetry).[][] It occurs in large readily cleavable crystals, easily divisible into rhombs, and is remarkable for its double refraction.[][1]

A Mine of Iceland Spar.

A mine of Iceland Spar

Historically, the double-refraction property of this crystal was important to understanding the nature of light as a wave. This was studied at length by Christiaan Huygens and Isaac Newton.[] Sir George Stokes also studied the phenomenon.[2] Its complete explanation in terms of light polarization was published by Augustin-Jean Fresnel in the 1820s.[3]

Mines producing Iceland spar include many mines producing related calcite and aragonite as well as those famously in Iceland,[4] productively in the greater Sonoran desert region as in Santa Eulalia, Chihuahua, Mexico[5] and New Mexico, United States,[6] as well as in the People's Republic of China.[7]

Viking "sunstone"

It has been speculated that the sunstone (Old Norse: *sólarsteinn*; a different mineral than the gem-quality sunstone) mentioned in medieval Icelandic texts was Iceland spar and that Vikings used its light-polarizing property to tell the direction of the sun on cloudy days, for navigational purposes.[8][9]

In 2007, Ramón Hegedüs and his colleagues from Eötvös Loránd University in Budapest, Hungary, confirmed that the polarization of sunlight in the Arctic can be detected under cloudy conditions. Their research is reported in "The Proceedings of the Royal Society."[10] Further research in 2011 by Ropers *et al.*,[11] confirms that identifying the direction of the sun to within a few degrees in both cloudy and twilight conditions was possible using the sunstone and the naked eye. The process involves moving the stone across the visual field to reveal a yellow entoptic pattern on the fovea of the eye, probably Haidinger's brush. The recovery of an Iceland spar sunstone from the Elizabethan ship *Alderney* that sank in 1592 suggests that the navigational technology may have persisted after the invention of the magnetic compass.[12]

In literature

Thomas Pynchon refers to the doubling property of Iceland spar in his 2006 novel *Against the Day*.[13] A section of the novel is entitled "Iceland Spar".[14]

Philip Pullman refers to the doubling property of Iceland spar[15] in his 2000 novel *The Amber Spyglass*, the third volume in the *His Dark Materials* trilogy.

References

[1] Miers, Henry A., *Mineralogy: an introduction to the scientific study of minerals*. Nabu Press. ISBN 1-177-85127-X Chap. 6, p. 128.

[2] Larmor, Joseph 2010. Retrieved January 2, 2011. *Memoir and scientific correspondence of the late Sir George Gabriel Stokes, bart., selected and arranged by Joseph Larmor* (http://books.google.com/books?id=Bg9DAAAAIAAJ&pg=PA269&lpg=PA269). Nabu Press. ISBN 1-177-14275-9 p. 269.

[3] Whittaker, E. T., *A History of the Theories of Aether and Electricity*. Dublin University Press, 1910.

[4] Russell, Daniel E . 17 February 2008. Retrieved December 31, 2010. " Helgustadir Iceland Spar Mine (http://www.mindat.org/article.php/190/Helgustadir+Iceland+Spar+Mine)" *mindat.org*

[5] Retrieved January 2, 2011. " Calcite (http://granitegap.com/Minerals/Featured-Minerals/Calicite.aspx)"*Granite Gap* "Several variety names exist for calcite. Iceland Spar is an ice-clear variety that demonstrates the effect of double refraction or birefringence ... Young

mountain ranges in Mexico and South America also host fine localities for calcite. They include Chihuahua, Chihuahua; the Santa Eulalia Dist., Chihuahua; Mapimí, Durango; Guanajuato, Guanajuato; and Charcas, San Luis Potosí; all Mexico"

[6] Kelley, Vincent C. 1940. Retrieved December 31, 2010. " Iceland Spar in Mew Mexico (http://www.minsocam.org/msa/collectors_corner/arc/nmcalcite.htm)". *American Mineralogist*, Volume 25, pp. 357-367

[7] WANG Jing-teng, CHEN Hen-shui, YANG En-lin,WU Bo. 2009. Retrieved January 3, 2011. " Geological Characteristics of Iceland Spar Mineral Deposit of Mashan District in Guizhou (http://en.cnki.com.cn/Article_en/CJFDTOTAL-KJQB200933061.htm)". *China National Knowledge Infrastructure*, P619.2

[8] *The Viking Sunstone* (http://www.polarization.com/viking/viking.html), from Polarization.net. Retrieved February 8, 2007.

[9] Karlsen, Leif K. 2003. *Secrets of the Viking Navigators*. One Earth Press. ISBN 978-0-9721515-0-4 220 pp.

[10] Hegedüs, Ramón, Åkesson, Susanne; Wehner, Rüdiger and Horváth, Gábor. 2007. "Could Vikings have navigated under foggy and cloudy conditions by skylight polarization? On the atmospheric optical prerequisites of polarimetric Viking navigation under foggy and cloudy skies". *Proc. R. Soc. A* **463** (2080): 1081–1095. . .

[11] Ropars, G. et al., 2011. A depolarizer as a possible precise sunstone for Viking navigation by polarized skylight. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science. Available at: http://rspa.royalsocietypublishing.org/content/early/2011/10/28/rspa.2011.0369.abstract [Accessed December 5, 2011].

[12] http://news.discovery.com/earth/rocks-fossils/viking-sunstone-shipwreck-130311.htm[Megan Gannon, "First evidence of Viking-like 'sunstone' found". newsdiscovery.com.] Accessed11 March 2013.

[13] Pynchon,Thomas, 2007. *Against the Day*. Penguin. ISBN 0-14-311256-2 p. 114.

[14] Ibid. pp. 119-428.

[15] Pullman, Philip, 2007. *The Amber Spyglass, Deluxe 10th Anniversary Edition*. Knopf. ISBN 0-375-84673-5 p. 226.

External links

- Calcite (http://www1.newark.ohio-state.edu/Professional/OSU/Faculty/jstjohn/Minerals/Calcite.htm)

Sunstone (medieval)

The **sunstone** (Icelandic: *sólarsteinn*) is a type of mineral attested in several 13th–14th century written sources in Iceland, one of which describes its use to locate the sun in a completely overcast sky. Sunstones are also mentioned in the inventories of several churches and one monastery in 14th–15th century Iceland. A theory exists that the sunstone had polarizing attributes and was used as a navigation instrument by seafarers in the Viking Age.[1]

A stone found in Alderney amid the wreckage of a 16th-century warship in early 2013 may lend evidence of the existence of sunstones as navigational devices.[2]

Iceland spar, possibly the Icelandic medieval sunstone used to locate the sun in the sky when obstructed from view.

Sources

One medieval source in Iceland, "Rauðúlfs þáttr",[3][4] mentions the sunstone as a mineral by means of which the sun could be located in an overcast and snowy sky by holding it up and noting where it emitted, reflected or transmitted light (*hvar geislaði úr honum*).[5] Sunstones are also mentioned in *Hrafns saga Sveinbjarnarsonar* (13th century)[6] and in church and monastic inventories (14th–15th century) without discussing their attributes. The sunstone texts of *Hrafns saga Sveinbjarnarsonar* were copied to all four versions of the medieval hagiography *Guðmundar saga*

góða.[7]

The description in "Rauðúlfs þáttr" of the use of the sunstone is as follows:

Thorsteinn Vilhjalmsson translation:	In Icelandic:
The weather was thick and snowy as Sigurður had predicted. Then the king summoned Sigurður and Dagur (Rauðúlfur's sons) to him. The king made people look out and they could nowhere see a clear sky. Then he asked Sigurður to tell where the sun was at that time. He gave a clear assertion. Then the king made them fetch the solar stone and held it up and saw where light radiated from the stone and thus directly verified Sigurður' s prediction.[8]	"Veður var þykkt og drífanda sem Sigurður hafði sagt. Þá lét konungur kalla til sín Sigurð og Dag. Síðan lét konungur sjá út og sá hvergi himin skýlausan. Þá bað hann Sigurð segja hvar sól mundi þá komin. Hann kvað glöggt á. Þá lét konungur taka sólarstein og hélt upp og sá hann hvar geislaði úr steininum og markaði svo beint til sem Sigurður hafði sagt".[9]

Allegorical nature of the medieval texts

Two of the original medieval texts on the sunstone are allegorical. Hrafns saga Sveinbjarnarsonar contains a burst of purely allegorical material associated with Hrafn's slaying. This involves a celestial vision with three highly cosmological knights, recalling the horsemen of the Apocalypse.[6] It has been suggested[10] that the horsemen of Hrafns saga contain allegorical allusions to the winter solstice and the four elements as an omen of Hrafn's death, where the sunstone also appears.

"Rauðúlfs þáttr", a tale of Saint Olav, and the only medieval source mentioning how the sunstone was used, is a thoroughly allegorical work.[11] A round and rotating house visited by Olav has been interpreted as a model of the cosmos and the human soul,[12] as well as a prefiguration of the Church.[13] The intention of the author was to achieve an apotheosis of St. Olav, through placing him in the symbolic seat of Christ.[11] The house belongs to the genre of "abodes of the sun," which seemed widespread in medieval literature.[4] St. Olav used the sunstone to confirm the time reckoning skill of his host right after leaving this allegorical house. He held the sunstone up against the snowy and completely overcast sky and noted where light was emitted from it (the Icelandic words used do not make it clear whether the light was reflected by the stone, emitted by it or transmitted through it). It has been suggested[10][14] that in Rauðúlfs þáttr the sunstone was used as a symbol of the Virgin, following a widespread tradition in which the virgin birth of Christ is compared with glass letting a ray of the sun through.[15]

The allegories of the above mentioned texts exploit the symbolic value of the sunstone, but the church and monastic inventories, however, show that something called sunstones did exist as physical objects in Iceland.[16] The presence of the sunstone in "Rauðúlfs þáttr" may be entirely symbolic[17] but its use is described in sufficient detail to show that the idea of using a stone to find the sun's position in overcast conditions was commonplace.[10]

Possibility of sunstones for orientation and navigation

Danish archaeologist Thorkild Ramskou posited that the sunstone could have been one of the minerals (cordierite or Iceland spar) that polarize light and by which the azimuth of the sun can be determined in a partly overcast sky or when the sun is just below the horizon.[1][18] The principle is used by many animals[19] and polar flights applied the idea before more advanced techniques became available.[20][21] Ramskou further conjectured that the sunstone could have aided navigation in the open sea in the Viking period. This idea has become very popular,[22] and although no records of the use of a sunstone for navigation exist in the medieval literature, research as to how a sunstone could be used in nautical navigation continues.

Research in 2011 by Ropers et al.,[23] confirms that one can identify the direction of the sun to within a few degrees in both cloudy and twilight conditions using the sunstone and the naked eye. The process involves moving the stone across the visual field to reveal a yellow entoptic pattern on the fovea of the eye. Alternatively a dot can be placed on top of crystal so that when you look at it from below, two dots appear, because the light is “depolarised” and

fractured along different axes. The crystal can then be rotated until the two points have the same luminosity. The angle of the top face now gives the direction of the sun.

The recovery of an Iceland spar sunstone from the Elizabethan ship near Alderney (which sank in 1592) suggests the possibility that the navigational technology may have persisted after the invention of the magnetic compass.[24] Although the stone was found near a navigational instrument, its use remains uncertain.[25]

Beyond nautical navigation, a polarizing crystal would have been useful as a sundial, especially at high latitudes with extended hours of twilight, in mountainous areas, or in partly overcast conditions. This use would require the polarizing crystal to be used in conjunction with known landmarks; churches and monasteries would have valued such an object as an aid to keep track of the canonical hours.[10]

References

[1] Ramskou, Thorkild. 1967. *Solstenen*. Skalk. ISBN 91-29-56391-7. 2: 16–17.

[2] http://www.nytimes.com/aponline/2013/03/08/world/europe/ap-eu-britain-sunstone.html?hp

[3] Turville-Petre, Joan E. (Trans.) (1947). " The story of Rauð and his sons (http://vsnrweb-publications.org.uk/The Story Of Raud And His Sons.pdf). Payne Memorial Series II. *Viking Society for Northern Research. ISBN 0-404-60014-X.*

[4] Faulkes, Anthony. 1966. "Rauðúlfs þáttr: A study". *Studia Islandica* 25. Heimspekideild Háskóla Íslands og Bókaútgáfa Menningarsjóðs. Reykjavík. . 92 pp.

[5] Sample, Ian." Crystals may have aided Viking sailors (http://www.guardian.co.uk/science/2007/feb/07/uknews.sciencenews1)". *Guardian* (Manchester, UK) p. 8. 7 February 2007. Retrieved December 27, 2010. "*Tests aboard a research vessel in the Arctic ocean found that certain crystals can be used to reveal the position of the sun, a trick that would have allowed early explorers to ascertain their position and navigate, even if the sky was obscured by cloud or fog.*"

[6] Helgadóttir, Guðrún P (ed.). 1987. *Hrafns Saga Sveinbjarnarsonar*. Oxford: Clarendon Press. ISBN 0-19-811162-2. 267 pp.

[7] Karlsson, Stefán (ed.).1983. *Guðmundar sögur biskups I: Ævi Guðmundar biskups, Guðmundar saga A. Editiones Arnamagnæanæ, Series B* (**6**). København: C.A. Reitzels Forlag. ISBN 87-7421-387-3. 262 pp.

[8] Vilhjalmsson, Thorsteinn. 1997. " Time and Travel in Old Norse Society (http://www.raunvis.hi.is/~thv/t_t.html)". *Disputatio*, (II): 89–114.

[9] Johnsen, Oscar Albert and Jón Helgason (eds.). 1941. *Saga Óláfs konungs hins helga. Den store saga om Olav den hellige. Efter pergamenthandskrift i Kungliga Biblioteket i Stockholm nr. 2 4to med varianter fra andre handskrifter*. ("Saga of King Olaf the Holy. The great saga of Olav the Holy. After the parchment manuscript no. 2 4to in the Royal Library in Stockholm with variants from other manuscripts.") Oslo: Norsk Historisk Kjeldeskrifts-Institutt, Vol. II. pp. 670–1

[10] Einarsson, Árni. 2010. Sólarsteinninn: tæki eða tákn. (Summary in English: Sunstone: fact or fiction). *Gripla* **21** (1) 281–97 Árni Magnússon Institute. .

[11] Einarsson, Árni. 1997. "Saint Olaf's dream house. A medieval cosmological allegory". *Skáldskaparmál* 4: 179–209, Reykjavík: Stafaholt.

[12] Einarsson, Árni. 2001. The symbolic imagery of Hildegard of Bingen as a key to the allegorical Raudulfs thattr in Iceland. *Erudiri Sapientia*, Studien zum Mittelalter und zu seiner Rezeptionsgeschichte (Studies on the Middle Ages and their reception history); II: 377–400.

[13] Loescher, G. 1981. "Rauðúlfs þáttr". *Zeitschrift für deutsches Altertum und Deutsche Literatur* (*ZfDA*) 110: 253-266.

[14] Bragason, Úlfar 1988. "The structure and meaning of Hrafns saga Sveinbjarnarsonar". *Scandinavian Studies* 60: 267–292.

[15] Breeze, Andrew. 1999. " The Blessed Virgin and the Sunbeam Through Glass (http://www.celt.dias.ie/publications/celtica/c23/c23-19.pdf)". *Celtica* 23: 19–29.

[16] Foote, Peter G. 1956. "Icelandic sólarsteinn and the Medieval Background". Arv. Nordic Yearbook of Folklore. **12**: 26-40.

[17] Schnall, Uwe. 1975. *Navigation der Wikinger. Nautische Probleme der Wikingerzeit im Spiegel der schriftlichen Quellen. Schr. Deutsch. Schiffahrtsmus*. ("*Navigation of the Vikings: Nautical Problems of the Viking Age in the Light of the Written Sources. Writings of the German Maritime Museum*"). Band 6. Oldenburg and Hamburg: Stalling, p. 196. ISBN 3-7979-1871-2.

[18] Ramskou, Thorkild. 1969. *Solstenen – Primitiv Navigation i Norden för Kompasset*. Köbenhavn: Rhodos. 95 pp.

[19] Horváth, Gábor and Dezsö Varjú. 2004. *Polarized Light in Animal Vision: Polarization Patterns in Nature*. Springer. pp. 447. ISBN 3-540-40457-0.

[20] Moody, Alton B. 1950. "The Pfund Sky Compass"; (via). *Navigation*. **2** (7): 234–239. .

[21] Rogers, Francis M. 1971. " Precision Astrolabe Portuguese Navigators and Transoceanic Navigation - [[Paul Kollsman|Kollsmann (http://fer3.com/arc/img/102218.sky compass.pdf)] Sky Compass]". *Academia Internacional da Cultura Portugeusa* (Lisbon, Portugal) pp. 288-291. Retrieved December 29, 2010.

[22] Hegedüs, Ramón, Åkesson, Susanne; Wehner, Rüdiger and Horváth, Gábor. 2007. "Could Vikings have navigated under foggy and cloudy conditions by skylight polarization? On the atmospheric optical prerequisites of polarimetric Viking navigation under foggy and cloudy skies". *Proc. R. Soc. A* **463** (2080): 1081–1095. . .

[23] Ropars, G. et al., 2011. A depolarizer as a possible precise sunstone for Viking navigation by polarized skylight. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Science. Available at: http://rspa.royalsocietypublishing.org/content/early/2011/10/

28/rspa.2011.0369.abstract [Accessed December 5, 2011].

[24] http://www.rawstory.com/rs/2013/03/05/shipwreck-may-contain-near-mythical-viking-navigation-aid/

[25] *Researchers may have found a Viking sunstone,* CBS News, March 8, 2013 (http://www.cbsnews.com/8301-205_162-57573239/researchers-may-have-found-a-viking-sunstone/)

External links

- The Fabled Viking Sunstone (http://www.nordskip.com/vikingcompass.html#sun)
- The Viking Sunstone Is the legend of the Sun-Stone true ? (http://www.polarization.com/viking/viking.html)

Sunstone

Sunstone	
General	
Category	Crystal
Formula (repeating unit)	sodium calcium aluminum silicate $(Ca,Na)((Al,Si)_2Si_2O_8)$
Identification	
Color	clear, yellow, red, green, blue, and copper shiller
Crystal habit	Euhedral Crytals, Granular
Crystal system	Triclinic
Twinning	Lamellar
Cleavage	001
Fracture	[
Diaphaneity	Transparent to Translucent
Density	2.64–2.66
Optical properties	Double Refractive:
Refractive index	1.525–1.58
Pleochroism	1

Sunstone is a plagioclase feldspar, which when viewed from certain directions exhibits a brilliant spangled appearance; this has led to its use as a gemstone. It has been found in Southern Norway, and in some United States localities. It is the official gemstone of Oregon.

Properties

Unpolished sunstone

The optical effect appears to be due to reflections from inclusions of red copper, in the form of minute scales, which are hexagonal, rhombic, or irregular in shape, and are disposed parallel to the principal cleavage-plane. These inclusions give the stone an appearance something like that of aventurine, hence sunstone is known also as "aventurine-feldspar." The optical effect called shiller and the color in Oregon Sunstone is due to copper. The middle part of this crystal sparkles, and usually the color is darkest in the middle and becomes lighter toward the outer edges.

The feldspar which usually displays the aventurine appearance is oligoclase, though the effect is sometimes seen in orthoclase: hence two kinds of sunstone are distinguished as "oligoclase sunstone" and "orthoclase sunstone."

Distribution

Sunstone was not common until recently. Previously the best-known locality being Tvedestrand, near Arendal, in south Norway, where masses of the sunstone occur embedded in a vein of quartz running through gneiss.

Other locations include near Lake Baikal in Siberia, and several United States localities—notably at Middletown Township, Delaware County, Pennsylvania, Lakeview, Oregon, and Statesville, North Carolina.

The "orthoclase sunstone" variant has been found near Crown Point and at several other localities in New York, as also at Glen Riddle in Delaware County, Pennsylvania, and at Amelia Courthouse, Amelia County, Virginia.

Sunstone is also found in Pleistocene basalt flows at Sunstone Knoll in Millard County, Utah.[1]

Oregon sunstone

Various gem colors of Oregon sunstone

A variety known as *Oregon sunstone* is found in Harney County, Oregon and in eastern Lake County north of Plush. Oregon sunstone contains inclusions of copper crystals. Oregon sunstones can be up to three inches wide. The copper leads to variant color within some stones, where turning one stone will result in manifold hues: the more copper within the stone, the darker the complexion.[2]

On August 4, 1987, the Oregon State Legislature designated Oregon sunstone as its state gemstone by joint resolution.[3]

References

[1] Sunstones at Sunstone Knoll, Millard County. (http://geology.utah.gov/utahgeo/rockmineral/collecting/sunstone.htm) Utah Geological Survey, accessed September 14, 2007.

[3] Chapter 186 – State Emblems; State Boundary (http://www.leg.state.or.us/ors/186.html) 2005 Oregon Revised Statutes

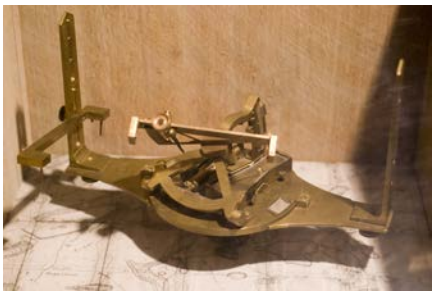
This article incorporates text from a publication now in the public domain: Chisholm, Hugh, ed. (1911). *Encyclopædia Britannica* (11th ed.). Cambridge University Press.

External links

- Mineralogy Database (http://webmineral.com/data/Oligoclase.shtml)
- Saab, Patricia. Oregon Sunstone (http://www.oregonencyclopedia.org/entry/view/oregon_sunstone/) in the *Oregon Encyclopedia*

Solar compass

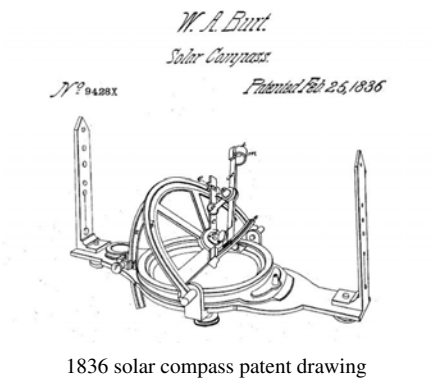
The **solar compass**, an astronomical instrument, was first invented and made by William Austin Burt.[1] He patented it on February 25, 1836, in the United States Patent Office as No 9428X [2].[3] It received a medal at the Great Exhibition of 1851.[4] The Calumet and Hecla Mine, largest copper mine in the world, was discovered through the use of Burt's solar compass.[4]



William Burt Solar Compass

History

From the middle of the 19th century until late in the 20th century, the solar compass was widely employed for surveying land. Its original impetus was for use where magnetic compasses were susceptible to iron bearing minerals that made for inaccurate readings. It was then found to be superior to the magnetic compass even when local attraction was not a problem. Its close relative, a solar compass attachment to a surveyor's transit, was still a recommended method of obtaining direction in the 1973 manual of the US Bureau of Land Management.[5] Using the location of the sun, or occasionally the moon, with astronomical tables, the solar compass enabled surveyors to run more accurate lines, saving its user valuable time.



1836 solar compass patent drawing

Burt, a United States Deputy Surveyor, began surveying government lands in Michigan in 1833. While working in Wisconsin, where there were large deposits of iron ore, Burt experienced great difficulty in using his standard vernier scale compass. This motivated him to find a solution that was not dependent on magnetism and would not be influenced by earth's ore materials. With his mechanical abilities, he then devised and built the solar compass. Burt made a model of his instrument in 1835 to test its validity. The instrument was then submitted to a committee at the Franklin Institute in Philadelphia. They examined its principles and merits and ultimately awarded Burt twenty dollars in gold and the John Legacy Medal.[6] He improved on his surveying instrument and in 1840 re-submitted it to the Franklin Institute. The instrument was further improved over the years and in 1851 he exhibited that version at the Great Exhibition in London, where he was awarded another prize medal.[6] He then received another medal by jurors of Astronomical Instruments.[7]

When Burt's solar compass original patent of 1836 was about to expire, he went to Washington to apply for a renewal in 1850. The land commissioner committee, who consisted of senators from Michigan and other states, recognizing the value of Burt's solar compass in public land surveys, persuaded him to forego renewal and petition congress for suitable advance compensation. Burt did as was suggested to him on the faith he would get paid for his

patent of such a valuable instrument. However the compensation indicated did not materialize in Burt's lifetime or at any time thereafter. Since there was no patent on Burt's solar compass after 1850, instrument makers sold "Burt's solar compass" to surveyors.[8]

In the preface to his *Key to the Solar Compass and Surveyor's Companion* published in 1858 by his associate William S. Young, Burt refers to the many requests for such a book on how to use his solar compass. He explains a magnetic compass had problems with the true meridian at different localities. It also had problems from day to day with different readings from that expected as a constant or from previous readings. It was determined that a magnetic compass used as a surveying tool was interfered many times from the local attraction of iron ore. A much better guide for the surveyor than the magnetic needle compass was much needed. Burt's diligent hard work, persistence and perseverance ultimately paid off in the invention of the Solar or Astronomical Compass.[7]

Description

Burt's solar compass is a precision instrument made of brass with a solar attachment that allows surveyors to determine the true north direction by reference to the sun rather than by reference to the magnetic north pole.[6] It allowed surveyors to locate true north through viewing the sun and other astronomical observations and was not influenced by magnetism or iron ore or other ore materials.[4] The United States government required land surveys to be done by Burt's Solar compass; as in many cases the cost to accurately survey lands with heavy mineral deposits that interfered with normal instrumentation would have exceeded the value of the land.[4]

Burt's precision surveying instrument consists of three arcs: one for setting the latitude of the land; one for setting the declination of the sun; and one for setting the hour of the day. The instrument has two main plates, the upper and the lower. On the lower plate is placed the sights. This plate revolves underneath the upper plate on a centre. The upper plate remains stationary. The lower plate may be clamped in any position to the upper plate.[9][10]

There is a graduated ring on the lower plate which covered by the upper plate, except two openings at opposite points. Here there are verniers to read angles. On the upper plate is placed a needle box, having divisions for the north end the needle only of about 36 degrees, with a vernier to read the needle's variation. Upon this plate, is placed the solar apparatus. It consists of a latitude arc, declination arc, and an hour arc. There are also two levels, placed right angles with each other, together with other necessary fixtures.[9][10]

The latitude arc is that which is attached by screws to the plate. It stands nearly vertical to the plate. The hour arc lies partly horizontal over the levels, and the declination arc placed upon a revolving limb, above the plate, and other fixtures of the solar apparatus. On this revolving limb is placed another movable limb, which turns on a joint at one end, and the other end, with a vernier, moves over the declination arc, with a clamp screw, to clamp it to the sun's declination for the time being. At each end of this described limb, there is attached to it a small brass plate standing out at right angles with the limb, and into the upper side of one and the lower side of the other, is set a small convex lens. Opposite to each lens on the brass plates there is attached a small silver plate, by means of three small screws and on each of these, lines are drawn at a suitable distance apart to embrace the sun's image, which falls upon each from the lenses. It will be seen, by inspecting this part of the instrument, that it must be used one end towards the sun, when he has north declination, and the other end for south declination.[9][10]

To gain a better understanding of the set of parts of the solar apparatus just described one should pay particular attention to the apparent motion of the sun or stars, around the earth, regarding the earth as lies center of their daily revolutions. A distinct view of the apparent conical motion of the sun, when it has north or south declination, is necessary, in order to understand how the movable parts of the solar apparatus may be adjusted to trace the sun, in its apparent course, while the sights of the sun compass remains stationary. If one imagined he was at the Earth's equator and the sun had no declination, the sun would rise to him due east, and set due west. At noon the sun would be at the highest point, and in the lowest point at midnight. In other words, when the sun has no declination, its apparent revolutions are in a perfect plane with the Earth's equator.[9][10]

If a straight line were drawn from the rising sun to the setting sun, and from the sun at noon and at midnight, both of these lines would pass through the Earth's center and the equator would intersect these lines. This is not so when the sun has north or south declination because its apparent motion will have an angle to the above described plane or lines, with the Earth's center, equal to the amount of the sun's declination north or south. Then it will be seen, that when the sun has north or south declination, and the earth is regarded as the center of its revolutions the plane just mentioned becomes conical.[9][10]

This apparent conical motion of the sun may be further explained by the spoked wheels of a covered wagon. The rim representing the sun's apparent path, the hub, the earth, and the spokes, lines drawn from the sun's path. Then it may be seen that a line drawn from the sun to the Earth's center would pass north or south of the equator, equal in degree to its declination north or south. These apply to the apparent revolutions of the planets and fixed stars as well.[9][10]

The operation is as follows:

1. Set the sun's declination for that day, obtained by means of tables, on a scale attached perpendicular to the time dial.
2. Set the latitude on a scale in the alidade.
3. Set the approximate local time on a dial that rotates on a polar axis.
4. Orient the instrument, while remaining level, so the image of the sun appears between scribed lines on a screen below a lens. The time dial is fine adjusted to bring the image between lines perpendicular to the first set. The time axis will then point to the pole.
5. The pinnula (sighting vanes) may then be pointed to a terrestrial object and its bearing read from the angle scale.
6. The magnetic declination may be read from a compass attached to the base plate.[9][10]

References

[1] Mining and metallurgy, Issues 169-180 By American Institute of Mining and Metallurgical Engineers, p. cccxli Charles S. Burt, the grandson of William Austin Burt (http://books.google.com/books?id=YY3mAAAAMAAJ&pg=PR341&lpg=PR341&dq=Scientific+American+"Equatorial+Sextant"&source=bl&ots=ZjlpShWcp4&sig=i7tP9QIzSphpxt-apzoMVg-IsL4&hl=en&ei=d_jaTKaGB4KOnweP6rXeAQ&sa=X&oi=book_result&ct=result&resnum=4&ved=0CDwQ6AEwAw#v=onepage&q=Scientific American "Equatorial Sextant"&f=false)

[2] http://www.google.com/patents?id=_YwCAAAAEBAJ&pg=PA1&dq=patent:X9428&source=gbs_selected_pages&cad=1#v=onepage&q&f=false

[3] Solar Compass (http://americanhistory.si.edu/collections/surveying/type.cfm?typeid=17)

[4] Farmer, p. 362

[5] http://www.blm.gov/cadastral/Manual/73man/id34.htm

[6] White, p. 367

[7] Burt, *Key to the Solar Compass and Surveyor's Companion* preface

[8] Fuller, pp. 175-193 *William Austin Burt- inventor, by Horace Eldon Burt (Chicago)* biography

[9] *Description of the Solar Compass* , pp. 3-19

[10] *A Key to the Solar Compass, and Surveyor's Companion*, pp. 9-11

Sources

- Burt, William A. *Description of the Solar Compass* (Detroit, 1844).
- Burt, William A. *A Key to the Solar Compass, and Surveyor's Companion*, third edition, publisher D. van Nostrand, (New York, 1873).
- Burt, John, *History of the Solar Compass Invented by Wm. A. Burt* (Detroit, 1878).
- Farmer, Silas, *The history of Detroit and Michigan,* 1899
- Fuller, George Newman, *Michigan history,* Volume 6, Michigan Department of State, 1922
- Tuttle, Charles Richard, *General History of the state of Michigan with biographical sketches*, R. D. S. Tyler & Co., Detroit Free Press Company, 1873
- White, James T., *Cyclopedia of American Biography*, volume xviii, 1922

External links

- Onsrud Manual, Appendix 5 - Solar Compass (http://jerrymahun.com/documents/onsrud/App5.pdf)
- Picture and description of Burt Solar Compass (http://www.wisconsinhistory.org/museum/artifacts/archives/002627.asp), Wisconsin Historical Society
- Solar Compass patent photo and transcription (http://www.surveyhistory.org/1836_solar_compass_patent1.htm)
- Patent 9428X Solar Compass (http://www.google.com/patents?id=_YwCAAAAEBAJ&printsec=abstract&zoom=4&source=gbs_overview_r&cad=0#v=onepage&q&f=false)

Astrocompass

An **astrocompass** is a navigational tool for determining the direction of true north through the positions of various astronomical bodies.

There are certain circumstances when magnetic compasses and gyrocompasses are unreliable. The most obvious is in polar regions, where the force exerted on the needle of a magnetic compass is nearly vertical and gyrocompasses become unstable due to the rotation of the Earth. Magnetic compasses are also susceptible to disruption from magnetic fields other than the Earth's, such as those produced by the hulls of some metal vehicles or craft. Before the advent of electronic navigational aids such as GPS the most reliable way to ascertain north in such circumstances was through the use of an astrocompass.

Astrocompass mk. II

Principle of use

The Earth's axis of rotation remains, for all intents and purposes, stationary throughout the year. Thus, with knowledge of the current time and geographical position in the form of latitude and longitude, which are set on the instrument using dials, an astrocompass can be sighted on to any astronomical object with a known position to give an extremely accurate reading.

In its most basic form, the astrocompass consists of a base plate marked with the points of the compass, with a mechanism known as an equatorial drum mounted on it. On this drum is a set of adjustable sights and a scale of declination. More advanced versions may have built-in chronometers or default settings for bodies such as the Sun.

To use the compass, the base plate is first levelled with the horizon then pointed roughly to what the user believes to be north. The equatorial drum is then tilted in relation to this base according to the local latitude. The sights are then set using the local hour angle and the declination of whatever astronomical body is being used. Once all these settings have been made, the astrocompass is simply turned until the astronomical body is visible in the sights: it will then be precisely aligned to the points of the compass. Because of this procedure, an astrocompass requires its user to be in possession of a nautical almanac or similar astronomical tables, one of its chief disadvantages.

Historical uses

Astrocompasses only became useful following the invention of the marine chronometer, without which it is almost useless for navigation. Even then, they saw only limited use, with first magnetic compasses and then gyrocompasses being preferred in almost all cases. Polar exploration was one of the fields in which the astrocompass saw the most use, for the reasons described above. They have also been used throughout history in other climes to check the accuracy of other forms of compasses: they saw use, for example, in the North African Campaign of World War 2.

GPS and other similar forms of electronic navigation aids mean that the astrocompass is now functionally obsolete anywhere except for areas very close to the poles where GPS coverage is not available and there are no current electronic navigation aids.

Operation

The operation is as follows:

1. Getting the local time (by means of a clock)
2. Setting the latitude
3. Setting (in the alidade) the star's local hour angle (LHA) for that day obtained by means of tables or a computer program
4. Pointing the compass pinnula to the star (sun or moon)
5. Reading the true course on the limb

References

- 'How it Works, Part 6' *Marshall Cavendish Limited 1974*

Compass

A simple dry magnetic portable compass.

A **compass** is a **navigational instrument** that shows directions in a frame of reference that is stationary relative to the surface of the earth. The frame of reference defines the four *cardinal directions* (or *points*) – north, south, east, and west. Intermediate directions are also defined. Usually, a diagram called a compass rose, which shows the directions (with their names usually abbreviated to initials), is marked on the compass. When the compass is in use, the rose is aligned with the real directions in the frame of reference, so, for example, the "N" mark on the rose really points to the north. Frequently, in addition to the rose or sometimes instead of it, angle markings in degrees are shown on the compass. North corresponds to zero degrees, and the angles increase clockwise, so east is 90 degrees, south is 180, and west is 270. These numbers allow the compass to show azimuths or bearings, which are commonly stated in this notation.

The magnetic compass was first invented as a device for divination as early as the Chinese Han Dynasty (since about 206 BC).[][1][] The compass was used in Song Dynasty China by the military for navigational orienteering by 1040-1044,[2][3][4] and was used for

maritime navigation by 1111 to 1117.[] The use of a compass is recorded in Western Europe between 1187 and 1202,[5][6][] and in Persia in 1232.[7] The dry compass was invented in Europe around 1300.[8] This was supplanted in the early 20th century by the liquid-filled magnetic compass.[9]

A smartphone that can be used as a compass because of the magnetometer inside.

Types of compasses

There are two widely used and radically different types of compass. The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles.[10] Simple compasses of this type show directions in a frame of reference in which the directions of the magnetic poles are due north and south. These directions are called *magnetic north* and *magnetic south*. The gyro compass (sometimes spelled with a hyphen, or as one word) contains a rapidly spinning wheel whose rotation interacts dynamically with the rotation of the earth so as to make the wheel precess, losing energy to friction until its axis of rotation is parallel with the earth's. The wheel's axis therefore points to the earth's rotational poles, and a frame of reference is used in which the directions of the rotational poles are due north and south. These directions are called *true north* and *true south*, respectively. The astrocompass works by observing the direction of stars and other celestial bodies.

A military compass that was used during World War I.

There are other devices which are not conventionally called compasses but which do allow the true cardinal directions to be determined. Some GPS receivers have two or three antennas, fixed some distance apart to the structure of a vehicle, usually an aircraft or ship. The exact latitudes and longitudes of the antennas can be determined simultaneously, which allows the directions of the cardinal points to be calculated relative to the heading of the aircraft (the direction in which its nose is pointing), rather than to its direction of movement, which will be different if there is a crosswind. They are said to work "like a compass", or "as a compass".

Even a GPS device or similar can be used as compass, since if the receiver is being moved, even at walking pace, it can follow the change of its position, and hence determine the compass bearing of its direction of movement, and thence the directions of the cardinal points relative to its direction of movement. A much older example was the Chinese south-pointing chariot, which worked like a compass by directional dead reckoning. It was initialized by hand, possibly using astronomical observations e.g. of the Pole Star, and thenceforth counteracted every turn that was made to keep its pointer aiming in the desired direction, usually to the south. Watches and sundials can also be used to find compass directions. See their articles for details.

A recent development is the electronic compass which detects the direction without potentially fallible moving parts. This may use a fibre optic gyrocompass or a magnetometer. The magnetometer frequently appears as an optional subsystem built into hand-held GPS receivers and mobile phones. However, magnetic compasses remain popular, especially in remote areas, as they are relatively inexpensive, durable, and require no power supply.[11]

Magnetic compass

The magnetic compass consists of a magnetized pointer (usually marked on the North end) free to align itself with Earth's magnetic field. A compass is any magnetically sensitive device capable of indicating the direction of the magnetic north of a planet's magnetosphere. The face of the compass generally highlights the cardinal points of north, south, east and west. Often, compasses are built as a stand alone sealed instrument with a magnetized bar or needle turning freely upon a pivot, or moving in a fluid, thus able to point in a northerly and southerly direction.

The compass greatly improved the safety and efficiency of travel, especially ocean travel. A compass can be used to calculate heading, used with a sextant to calculate latitude, and with a marine chronometer to calculate longitude. It thus provides a much improved navigational capability that has only been recently supplanted by modern devices such as the Global Positioning System (GPS).

How a magnetic compass works

A compass functions as a pointer to "magnetic north" because the magnetized needle at its heart aligns itself with the lines of the Earth's magnetic field. The magnetic field exerts a torque on the needle, pulling one end or *pole* of the needle toward the Earth's North magnetic pole, and the other toward the South magnetic pole. The needle is mounted on a low-friction pivot point, in better compasses a jewel bearing, so it can turn easily. When the compass is held level, the needle turns until, after a few seconds to allow oscillations to die out, one end points toward the North magnetic pole.

An inexpensive compass, aligned so that its needle points through the "North" mark on its compass card.

A magnet or compass needle's "north" pole is defined as the one which is attracted to the North magnetic pole of the Earth, in northern Canada. Since opposite poles attract ("north" to "south") the North magnetic pole of the Earth is actually the *south* pole of the Earth's magnetic field.[12][13][14] The compass needle's north pole is always marked in some way: with a distinctive color, luminous paint, or an arrowhead.

Instead of a needle, professional compasses usually have bar magnets glued to the underside of a disk pivoted in the center so it can turn, called a "compass card", with a "compass rose" showing the cardinal points and degrees marked on it. Better compasses are "*liquid-filled*"; the chamber containing the needle or disk is filled with a liquid whose purpose is to damp the oscillations of the needle so it will settle down to point to North more quickly, and also to protect the needle or disk from shock.

In navigation, directions on maps are expressed with reference to *geographical* or *true north*, the direction toward the Geographical North Pole, the rotation axis of the Earth. Since the Earth's magnetic poles are near, but are not at

the same locations as its geographic poles, a compass does not point to true north. The direction a compass points is called *magnetic north*, the direction of the North magnetic pole, located in northeastern Canada. Depending on where the compass is located on the surface of the Earth the angle between true north and magnetic north, called *magnetic declination* can vary widely, increasing the farther one is from the prime meridian of the Earth's magnetic field. The local magnetic declination is given on most maps, to allow the map to be oriented with a compass parallel to true north. Some magnetic compasses include means to manually compensate for the magnetic declination, so that the compass shows true directions.

In geographic regions near the magnetic poles, in northeastern Canada and Antarctica, variations in the Earth's magnetic field cause magnetic compasses to have such large errors that they are useless, so other instruments must be used for navigation.

The positions of the magnetic poles change over time on a time-scale that is not extremely long by human standards. Significant movements happen in a few years.

History

The compass was invented in China, during the Han Dynasty between the 2nd century BC and 1st century AD.[] The first compasses were made of lodestone, a naturally magnetized ore of iron.[] Ancient Chinese people found that if a lodestone was suspended so it could turn freely, it would always point in the same direction, toward the magnetic poles. Early compasses were used for geomancy "in the search for gems and the selection of sites for houses," but were later adapted for navigation during the Song Dynasty in the 11th century.[] Later compasses were made of iron needles, magnetized by striking them with a lodestone. The dry compass was invented in medieval Europe around 1300.[8] This was supplanted in the early 20th century by the liquid-filled magnetic compass.[9]

Navigation prior to the compass

Prior to the introduction of the compass, position, destination, and direction at sea were primarily determined by the sighting of landmarks, supplemented with the observation of the position of celestial bodies. On cloudy days, the Vikings may have used cordierite or some other birefringent crystal to determine the sun's direction and elevation from the polarization of daylight; their astronomical knowledge was sufficient to let them use this information to determine their proper heading.[15] For more southerly Europeans unacquainted with this technique, the invention of the compass enabled the determination of heading when the sky was overcast or foggy. This enabled mariners to navigate safely far from land, increasing sea trade, and contributing to the Age of Discovery.

Geomancy and feng shui

Magnetism was originally used, not for navigation, but for geomancy and fortune-telling by the Chinese. The earliest Chinese magnetic compasses were probably not designed for navigation, but rather to order and harmonize their environments and buildings in accordance with the geomantic principles of *feng shui*. These early compasses were made using lodestone, a special form of the mineral magnetite that aligns itself with the Earth’s magnetic field.[]

Based on Krotser and Coe's discovery of an Olmec hematite artifact in Mesoamerica, radiocarbon dated to 1400-1000 BC, astronomer John Carlson has hypothesized that the Olmec might have used the geomagnetic lodestone earlier than 1000 BC for geomancy, a method of divination, which if proven true, predates the Chinese use of magnetism for feng shui by a millennium.[16] Carlson speculates that the Olmecs used similar artifacts as a directional device for astronomical or geomantic purposes but does not suggest navigational usage. The artifact is part of a polished hematite (lodestone) bar with a groove at one end (possibly for sighting). The artifact now consistently points 35.5 degrees west of north, but may have pointed north-south when whole. Carlson's claims have been disputed by other scientific researchers, who have suggested that the artifact is actually a constituent piece of a decorative ornament and not a purposely built compass.[17] Several other hematite or magnetite artifacts have been found at pre-Columbian archaeological sites in Mexico and Guatemala.[18][19]

Navigational compass

The invention of the navigational compass is credited by scholars to the Chinese, who began using it for navigation sometime between the 9th and 11th century, "some time before 1050, possibly as early as 850."[] A common theory by historians,[][] suggests that the Arabs introduced the compass from China to Europe, although current textual evidence only supports the fact that Chinese use of the navigational compass preceded that of Europe and the Middle East.[2]

China

There is disagreement as to exactly when the compass was invented. These are noteworthy Chinese literary references in evidence for its antiquity:

Model of a Han Dynasty (206 BC–220 AD) south-indicating ladle or *sinan*. It is theorizedWikipedia:Avoid weasel words that the south-pointing spoons of the Han dynasty were magnetized lodestones.[]

- The earliest Chinese literature reference to **magnetism** lies in the 4th century BC writings of Wang Xu (鬼谷子): "The lodestone attracts iron."[20] The book also notes that the people of the state of Zheng always knew their position by means of a "south-pointer"; some authors suggest that this refers to early use of the compass.[][21]
- The first mention of a spoon, speculated to be a lodestone, observed **pointing in a cardinal direction** is a Chinese work composed between 70 and 80 AD (*Lunheng*), which records that "But when the south pointing spoon is thrown upon the ground, it comes to rest pointing at the south."[22] Within the text, the author Wang Chong describes the spoon as a phenomenon that he has personally observed.[23] Although the passage does not explicitly mention magnetism,[24] according to Chen-Cheng Yih, the "device described by Wang Chong has been widely considered to be the earliest form of the magnetic compass."[]
- The first clear account of **magnetic declination** occurs in the *Kuan Shih Ti Li Chih Meng* ("Mr. Kuan's Geomantic Instructor"), dating to 880.[] Another text, the *Chiu Thien Hsuan Nu Chhing Nang Hai Chio Ching* ("Blue Bag Sea Angle Manual") from around the same period, also has an implicit description of magnetic declination. It has been argued that this knowledge of declination requires the use of the compass.[]
- A reference to a magnetized needle as a "**mysterious needle**" appears in 923-926 in the *Chung Hua Ku Chin Chu* text written by Ma Kao. The same passage is also attributed to the 4th century AD writer Tshui Pao, although it is postulated that the former text is more authentic. The shape of the needle is compared to that of a tadpole, and may indicate the transition between "lodestone spoons" and "iron needles."[25]
- The earliest reference to a specific magnetic **direction finder** device for land navigation is recorded in a Song Dynasty book dated to 1040-44. There is a description of an iron "south-pointing fish" floating in a bowl of water, aligning itself to the south. The device is recommended as a means of orientation "in the obscurity of the night." The *Wujing Zongyao* (武經總要, "Collection of the Most Important Military Techniques") stated: "When troops encountered gloomy weather or dark nights, and the directions of space could not be distinguished...they made use of the [mechanical] south-pointing carriage, or the south-pointing fish."[3] This was achieved by heating of metal (especially if steel), known today as thermoremanence, and would have been capable of producing a weak state of magnetization.[3] While the Chinese achieved magnetic remanence and induction by this time, in both Europe and Asia the phenomenon was attributed to the supernatural and occult, until about 1600 when William Gilbert published his *De Magnete*.[]
- The first incontestable reference to a **magnetized needle** in Chinese literature appears in 1088.[4] The *Dream Pool Essays*, written by the Song Dynasty polymath scientist Shen Kuo, contained a detailed description of how geomancers magnetized a needle by rubbing its tip with lodestone, and hung the magnetic needle with one single strain of silk with a bit of wax attached to the center of the needle. Shen Kuo pointed out that a needle prepared

this way sometimes pointed south, sometimes north.

- The earliest explicit recorded use of a magnetic compass for **maritime navigation** is found in Zhu Yu's book *Pingchow Table Talks* (萍洲可談; Pingzhou Ketan) and dates from 1111 to 1117: *The ship's pilots are acquainted with the configuration of the coasts; at night they steer by the stars , and in the daytime by the sun. In dark weather they look at the south pointing needle*.[]

Thus, the use of a magnetic compass by the military for land navigation occurred sometime before 1044, but incontestable evidence for the use of the compass as a maritime navigational device did not appear until 1117.

The typical Chinese navigational compass was in the form of a magnetic needle floating in a bowl of water.[26] According to Needham, the Chinese in the Song Dynasty and continuing Yuan Dynasty did make use of a dry compass, although this type never became as widely used in China as the wet compass.[27] Evidence of this is found in the *Shilin guangji* ("Guide Through the Forest of Affairs"), published in 1325 by Chen Yuanjing, although its compilation had taken place between 1100 and 1250.[27] The dry compass in China was a dry suspension compass, a wooden frame crafted in the shape of a turtle hung upside down by a board, with the lodestone sealed in by wax, and if rotated, the needle at the tail would always point in the northern cardinal direction.[27] Although the European compass-card in box frame and dry pivot needle was adopted in China after its use was taken by Japanese pirates in the 16th century (who had in turn learned of it from Europeans),[28] the Chinese design of the suspended dry compass persisted in use well into the 18th century.[29] However, according to Kreutz there is only a single Chinese reference to a dry-mounted needle (built into a pivoted wooden tortoise) which is dated to between 1150 and 1250, and claims that there is no clear indication that Chinese mariners ever used anything but the floating needle in a bowl until the 16th-century.[26]

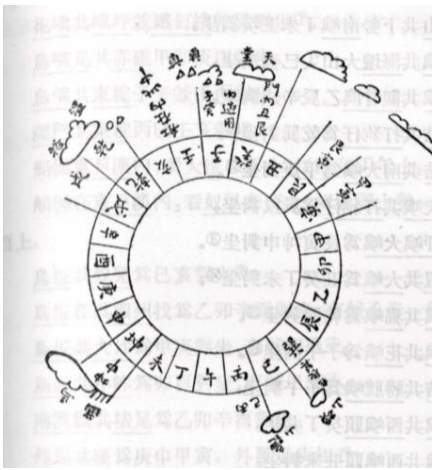
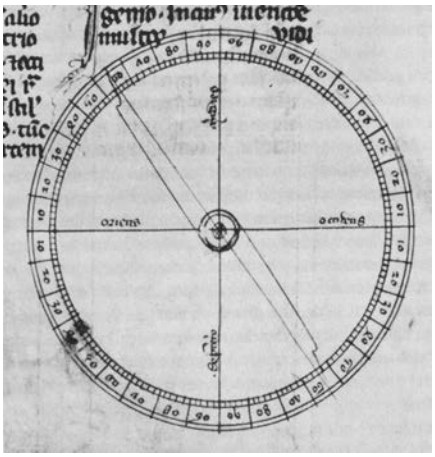


Diagram of a Ming Dynasty mariner's compass

The first recorded use of a 48 position mariner's compass on sea navigation was noted in *The Customs of Cambodia* by Yuan Dynasty diplomat Zhou Daguan, he described his 1296 voyage from Wenzhou to Angkor Thom in detail; when his ship set sail from Wenzhou, the mariner took a needle direction of “ding wei” position, which is equivalent to 22.5 degree SW. After they arrived at Baria,[30] the mariner took "Kun Shen needle", or 52.5 degree SW.[31] Zheng He's Navigation Map, also known as "The Mao Kun Map", contains a large amount of detail "needle records" of Zheng He's expeditions.[32]

There is a debate over the diffusion of the compass after its first appearance with the Chinese. At present, according to Kreutz, scholarly consensus is that the Chinese invention predates the first European mention by 150 years.[2] However, there are questions over diffusion, because of the apparent failure of the Arabs to function as possible intermediaries between East and West because of the earlier recorded appearance of the compass in Europe (1190)[5] than in the Muslim world (1232, 1242, and 1282).[7][33] The first European mention of a magnetized needle and its use among sailors occurs in Alexander Neckam's *De naturis rerum* (On the Natures of Things), written in 1190.[5][] The earliest reference to a compass in the Middle East is attributed to the Persians, who describe an iron fish-like compass in a talebook dating from 1232.[7] In the Arab world, the earliest reference comes in *The Book of the Merchants' Treasure*, written by one Baylak al-Kibjaki in Cairo about 1282.[33] Since the author describes having witnessed the use of a compass on a ship trip some forty years earlier, some scholars are inclined to antedate its first appearance accordingly. That the Arabic word for "Compass" (*al-konbas*) may be a derivation of the old Italian word for compass, is also used as evidence for the lack of diffusion from China to Europe. However, the Persian compass is described as fish-like, which is a characteristic of early Chinese compasses from the 11th century, suggesting transmission from China to Persia.[34]

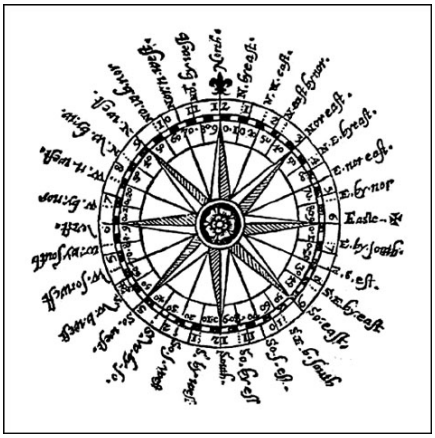
Medieval Europe



Pivoting compass needle in a 14th-century copy of *Epistola de magnete* of Peter Peregrinus (1269).

Alexander Neckam reported the use of a magnetic compass for the region of the English Channel in the texts *De utensilibus* and *De naturis rerum*,[6] written between 1187 and 1202, after he returned to England from France[] and prior to entering the Augustinian abbey at Cirencester.[] In 1269 Petrus Peregrinus of Maricourt described a floating compass for astronomical purposes as well as a dry compass for seafaring, in his well-known Epistola de magnete.[6] In the Mediterranean, the introduction of the compass, at first only known as a magnetized pointer floating in a bowl of water,[35] went hand in hand with improvements in dead reckoning methods, and the development of Portolan charts, leading to more navigation during winter months in the second half of the 13th century.[36] While the practice from ancient times had been to curtail sea travel between October and April, due in part to the lack of dependable clear skies during the Mediterranean winter, the prolongation of the sailing season resulted in a gradual, but sustained increase in shipping movement; by around 1290 the sailing season could start in late January or February, and end in December.[37] The additional few months were of considerable economic importance. For instance, it enabled Venetian convoys to make two round trips a year to the Levant, instead of one.[38]

At the same time, traffic between the Mediterranean and northern Europe also increased, with first evidence of direct commercial voyages from the Mediterranean into the English Channel coming in the closing decades of the 13th century, and one factor may be that the compass made traversal of the Bay of Biscay safer and easier.[39] However, critics like Kreutz feel that it was later in 1410 that anyone really started steering by compass.[40]



Navigational sailor's compass rose.

At present, according to Kreutz, "barring the discovery of new evidence, it seems clear the first Chinese reference to" the compass "antedates any European mention by roughly 150 years."[2] However, there are questions over diffusion, because of the apparent failure of the Arabs to function as possible intermediaries between East and West because of the earlier recorded appearance of the compass in Europe (1190)[5] than in the Muslim world (1232, 1242, and 1282).[7][33] This is countered by evidence of the temporal proximity of the Chinese navigational compass (1117) to its first appearance in Europe (1190) and the common shape of the early compass as a magnetized needle floating in a bowl of water.[5]

Islamic world

The earliest reference to an iron fish-like compass in the Islamic world occurs in a Persian talebook from 1232.[7] This fish shape was from a typical early Chinese design.[34] The earliest Arabic reference to a compass — in the form of magnetic needle in a bowl of water — comes from the Yemeni sultan and astronomer Al-Ashraf in 1282.[33] He also appears to be the first to make use of the compass for astronomical purposes.[41] Since the author describes having witnessed the use of a compass on a ship trip some forty years earlier, some scholars are inclined to antedate its first appearance in the Arab world accordingly.[7]

In 1300, another Arabic treatise written by the Egyptian astronomer and muezzin Ibn Simʿūn describes a dry compass for use as a "Qibla (Kabba) indicator" to find the direction to Mecca. Like Peregrinus' compass, however,

Ibn Simʿūn's compass did not feature a compass card.[6] In the 14th century, the Syrian astronomer and timekeeper Ibn al-Shatir (1304–1375) invented a timekeeping device incorporating both a universal sundial and a magnetic compass. He invented it for the purpose of finding the times of Salah prayers.[] Arab navigators also introduced the 32-point compass rose during this time.[42]

India

The compass was used in India for navigational purposes and was known as the matsya yantra, because of the placement of a metallic fish in a cup of oil.[43]

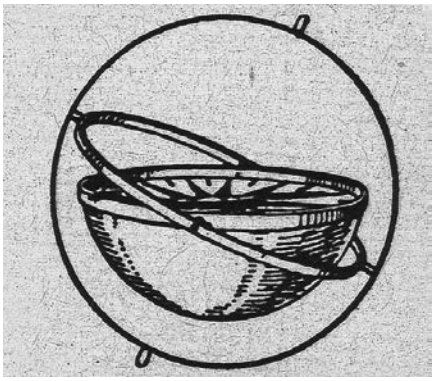
Medieval Africa

There is evidence that the distribution of the compass from China likely also reached eastern Africa by way of trade through the end of the Silk Road that ended in East African center of trade in Somalia and the Swahili city-state kingdoms.[44] There is evidence that Swahili maritime merchants and sailors acquired the compass at some point and used them for navigation of Swahili versions of dhows.[45]

Later developments

Dry compass

The dry mariner's compass was invented in Europe around 1300. The dry mariner's compass consists of three elements: A freely pivoting needle on a pin enclosed in a little box with a glass cover and a wind rose, whereby "the wind rose or compass card is attached to a magnetized needle in such a manner that when placed on a pivot in a box fastened in line with the keel of the ship the card would turn as the ship changed direction, indicating always what course the ship was on".[8] Later, compasses were often fitted into a gimbal mounting to reduce grounding of the needle or card when used on the pitching and rolling deck of a ship.



Early modern dry compass suspended by a gimbal (1570).

While pivoting needles in glass boxes had already been described by the French scholar Peter Peregrinus in 1269,[46] and by the Egyptian scholar Ibn Simʿūn in 1300,[6] traditionally Flavio Gioja (fl. 1302), an Italian pilot from Amalfi, has been credited with perfecting the sailor's compass by suspending its needle over a compass card, thus giving the compass its familiar appearance.[47] Such a compass with the needle attached to a rotating card is also described in a commentary on Dante's *Divine Comedy* from 1380, while an earlier source refers to a portable compass in a box (1318),[48] supporting the notion that the dry compass was known in Europe by then.[26]

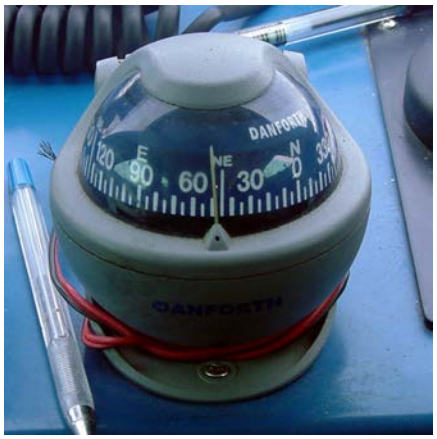
Bearing compass

Bearing compass (18th century).

A *bearing compass* is a magnetic compass mounted in such a way that it allows the taking of bearings of objects by aligning them with the lubber line of the bearing compass.[49] A *surveyor's compass* is a specialized compass made to accurately measure heading of landmarks and measure horizontal angles to help with map making. These were already in common use by the early 18th century and are described in the 1728 Cyclopaedia. The bearing compass was steadily reduced in size and weight to increase portability, resulting in a model that could be carried and operated in one hand. In 1885, a patent was granted for a hand compass fitted with a viewing prism and lens that enabled the user to accurately sight the heading of geographical landmarks, thus creating the *prismatic compass*.[50] Another sighting method was by means of a reflective mirror. First patented in 1902, the *Bézard compass* consisted of a field compass with a mirror mounted above it.[51][52] This arrangement enabled the user to align the compass with an objective while simultaneously viewing its bearing in the mirror.[51][53]

In 1928, Gunnar Tillander, a Swedish unemployed instrument maker and avid participant in the sport of orienteering, invented a new style of bearing compass. Dissatisfied with existing field compasses, which required a separate protractor in order to take bearings from a map, Tillander decided to incorporate both instruments into a single instrument. It combined a compass with a protractor built into the base. His design featured a metal compass capsule containing a magnetic needle with orienting marks mounted into a transparent protractor baseplate with a lubber line (later called a *direction of travel indicator*). By rotating the capsule to align the needle with the orienting marks, the course bearing could be read at the lubber line. Moreover, by aligning the baseplate with a course drawn on a map - ignoring the needle - the compass could also function as a protractor. Tillander took his design to fellow orienteers Björn, Alvid, and Alvar Kjellström, who were selling basic compasses, and the four men modified Tillander's design.[54] In December 1932, the Silva Company was formed with Tillander and the three Kjellström brothers, and the company began manufacturing and selling its Silva orienteering compass to Swedish orienteers, outdoorsmen, and army officers.[54][55][56][57]

Liquid compass



A surface mount, liquid-filled compass on a boat.

The liquid compass is a design in which the magnetized needle or card is damped by fluid to protect against excessive swing or wobble, improving readability while reducing wear. A rudimentary working model of a liquid compass was introduced by Sir Edmund Halley at a meeting of the Royal Society in 1690.[58] However, as early liquid compasses were fairly cumbersome and heavy, and subject to damage, their main advantage was aboard ship. Protected in a binnacle and normally gimbal-mounted, the liquid inside the compass housing effectively damped shock and vibration, while eliminating excessive swing and grounding of the card caused by the pitch and roll of the vessel. The first liquid mariner's compass believed practicable for limited use was patented by the Englishman Francis Crow in 1813.[59][60] Liquid-damped marine compasses for ships and small boats were occasionally used by the British Royal Navy from the 1830s through 1860, but the standard Admiralty compass remained a dry-mount type.[61] In the latter year, the American physicist and inventor Edward Samuel

Ritchie patented a greatly improved liquid marine compass that was adopted in revised form for general use by the United States Navy, and later purchased by the Royal Navy as well.[62]

Despite these advances, the liquid compass was not introduced generally into the Royal Navy until 1908. An early version developed by RN Captain Creak proved to be operational under heavy gunfire and seas, but was felt to lack navigational precision compared with the design by Lord Kelvin:

> Captain Creak's first step in the development of the liquid compass was to introduce a "card mounted on a float, with two thin and relatively short needles, fitted with their poles at the scientifically correct angular distances, and with the centre of gravity, centre of buoyancy, and the point of suspension in correct relation to each other...The compass thus designed rectified the defects of the Admiralty Standard Compass...with the additional advantage of considerable steadiness under heavy gunfire and in a seaway... The one defect in the compass as developed by Creak up to 1892 was that "for manoeuvring purposes it was inferior to Lord Kelvin's compass, owing to comparative sluggishness on a large alteration of course through the drag on the card by the liquid in which it floated...[9][63]

Typical aircraft-mounted magnetic compass.

However, with ship and gun sizes continuously increasing, the advantages of the liquid compass over the Kelvin compass became unavoidably apparent to the Admiralty, and after widespread adoption by other navies, the liquid compass was generally adopted by the Royal Navy as well.[9]

Liquid compasses were next adapted for aircraft. In 1909, Captain F.O. Creagh-Osborne, Superintendent of Compasses at the British Admiralty, introduced his *Creagh-Osborne* aircraft compass, which used a mixture of alcohol and distilled water to damp the compass card.[64][65] After the success of this invention, Capt. Creagh-Osborne adapted his design to a much smaller pocket model[66] for individual use[67] by officers of artillery or infantry, receiving a patent in 1915.[68]

In December 1932, the newly founded Silva Company of Sweden introduced its first baseplate or bearing compass that used a liquid-filled capsule to damp the swing of the magnetized needle.[54] The liquid-damped Silva took only four seconds for its needle to settle in comparison to thirty seconds for the original version.[54]

In 1933 Tuomas Vohlonen, a surveyor by profession, applied for a patent for a unique method of filling and sealing a lightweight celluloid compass housing or capsule with a petroleum distillate to dampen the needle and protect it from shock and wear caused by excessive motion.[69] Introduced in a wrist-mount model in 1936 as the Suunto Oy *Model M-311*, the new capsule design led directly to the lightweight liquid field compasses of today.[69]

History of non-navigational uses

Building orientation

Evidence for the orientation of buildings by the means of a magnetic compass can be found in 12th century Denmark: one fourth of its 570 Romanesque churches are rotated by 5-15 degrees clockwise from true east-west, thus corresponding to the predominant magnetic declination of the time of their construction.[70] Most of these churches were built in the 12th century, indicating a fairly common usage of magnetic compasses in Europe by then.[71]

Mining

The use of a compass as a direction finder underground was pioneered by the Tuscan mining town Massa where floating magnetic needles were employed for determining tunneling and defining the claims of the various mining companies as early as the 13th century.[72] In the second half of the 15th century, the compass became standard equipment for Tyrolian miners. Shortly afterwards the first detailed treatise dealing with the underground use of compasses was published by a German miner Rülein von Calw (1463–1525).[73]

Astronomy

Three astronomical compasses meant for establishing the meridian were described by Peter Peregrinus in 1269 (referring to experiments made before 1248)[74] In the 1300s, an Arabic treatise written by the Egyptian astronomer and muezzin Ibn Simʿūn describes a dry compass for use as a "Qibla indicator" to find the direction to Mecca. Ibn Simʿūn's compass, however, did not feature a compass card nor the familiar glass box.[6] In the 14th century, the Syrian astronomer and timekeeper Ibn al-Shatir (1304–1375) invented a timekeeping device incorporating both a universal sundial and a magnetic compass. He invented it for the purpose of finding the times of Salah prayers.[] Arab navigators also introduced the 32-point compass rose during this time.[42]

Modern compasses

Modern compasses usually use a magnetized needle or dial inside a capsule completely filled with a liquid (lamp oil, mineral oil, white spirits, purified kerosene, or ethyl alcohol is common). While older designs commonly incorporated a flexible rubber diaphragm or airspace inside the capsule to allow for volume changes caused by temperature or altitude, some modern liquid compasses utilize smaller housings and/or flexible capsule materials to accomplish the same result.[75] The liquid inside the capsule serves to dampen the movement of the needle, reducing oscillation time and increasing stability. Key points on the compass, including the north end of the needle are often marked with phosphorescent, photoluminescent, or self-luminous materials[76] to enable the compass to be read at night or in poor light. As the compass fill liquid is noncompressible under pressure, many ordinary liquid-filled compasses will operate accurately underwater to considerable depths.

A liquid-filled protractor or orienteering compass with lanyard.

Many modern compasses incorporate a baseplate and protractor tool, and are referred to variously as "orienteering", "baseplate", "map compass" or "protractor" designs. This type of compass uses a separate magnetized needle inside a rotating capsule, an orienting "box" or gate for aligning the needle with magnetic north, a transparent base containing map orienting lines, and a bezel (outer dial) marked in degrees or other units of angular measurement.[] The capsule is mounted in a transparent baseplate containing a *direction-of-travel* (DOT) indicator for use in taking bearings directly from a map.[]

Liquid filled lensatic compass.

Cammenga air filled lensatic compass.

Other features found on modern orienteering compasses are map and romer scales for measuring distances and plotting positions on maps, luminous markings on the face or bezels, various sighting mechanisms (mirror, prism, etc.) for taking bearings of distant objects with greater precision, "global" needles for use in differing hemispheres, adjustable declination for obtaining instant true bearings without resort to arithmetic, and devices such as clinometers for measuring gradients.[] The sport of orienteering has also resulted in the development of models with extremely fast-settling and stable needles for optimal use with a topographic map, a land navigation technique known as *terrain association*.[77]

The military forces of a few nations, notably the United States Army, continue to issue field compasses with magnetized compass dials or cards instead of needles. A magnetic card compass is usually equipped with an optical, lensatic, or prismatic sight, which allows the user to read the bearing or azimuth off the compass card while simultaneously aligning the compass with the objective (see photo). Magnetic card compass designs normally require a separate protractor tool in order to take bearings directly from a map.[][78]

The U.S. M-1950 military lensatic compass does not use a liquid-filled capsule as a dampening mechanism, but rather electromagnetic induction to control oscillation of it magnetized card. A "deep-well" design is used to allow the compass to be used globally with a card tilt of up to 8 degrees without impairing accuracy.[79] As induction forces provide less damping than liquid-filled designs, a needle lock is fitted to the compass to reduce wear, operated by the folding action of the rear sight/lens holder. The use of air-filled induction compasses has declined over the years, as they may become inoperative or inaccurate in freezing temperatures or extremely humid environments due to condensation or water ingress.[80]

Some military compasses, like the U.S. M-1950 (Cammenga 3H) military lensatic compass, the Silva 4b *Militaire*, and the Suunto M-5N(T) contain the radioactive material tritium ($_1H^3$) and a combination of phosphors.[81] The U.S. M-1950 equipped with self-luminous lighting contains 120 mCi (millicuries) of tritium. The purpose of the tritium and phosphors is to provide illumination for the compass, via radioluminescent tritium illumination, which does not require the compass to be "recharged" by sunlight or artificial light.[82] However, tritium has a half-life of only about 12 years,[83] so a compass that contains 120 mCi of tritium when new will contain only 60 when it is 12 years old, 30 when it is 24 years old, and so on. Consequently, the illumination of the display will fade.

Mariner's compasses can have two or more gimbaled magnets permanently attached to a compass card. These move freely on a pivot. A *lubber line*, which can be a marking on the compass bowl or a small fixed needle indicates the ship's heading on the compass card. Traditionally the card is divided into thirty-two points (known as *rhumb*s), although modern compasses are marked in degrees rather than cardinal points. The glass-covered box (or bowl) contains a suspended gimbal within a binnacle. This preserves the horizontal position.

Thumb compass

A **thumb compass** is a type of compass commonly used in orienteering, a sport in which map reading and terrain association are paramount. Consequently, most thumb compasses have minimal or no degree markings at all, and are normally used only to orient the map to magnetic north. Thumb compasses are also often transparent so that an orienteer can hold a map in the hand with the compass and see the map through the compass.

Thumb compass on left.

Gyrocompass

A *gyrocompass* is similar to a gyroscope. It is a non-magnetic compass that finds true north by using an (electrically powered) fast-spinning wheel and friction forces in order to exploit the rotation of the Earth. Gyrocompasses are widely used on ships. They have two main advantages over magnetic compasses:

- they find *true north*, i.e., the direction of Earth's rotational axis, as opposed to magnetic north,
- they are not affected by ferromagnetic metal (including iron, steel, cobalt, nickel, and various alloys) in a ship's hull. (No compass is affected by nonferromagnetic metal, although a magnetic compass will be affected by any kind of wires with electric current passing through them.)

Large ships typically rely on a gyrocompass, using the magnetic compass only as a backup. Increasingly, electronic fluxgate compasses are used on smaller vessels. However compasses are still widely in use as they can be small, use simple reliable technology, are comparatively cheap, often easier to use than GPS, require no energy supply, and unlike GPS, are not affected by objects, e.g. trees, that can block the reception of electronic signals.

Solid state compasses

Small compasses found in clocks, mobile phones, and other electronic devices are solid-state compasses, usually built out of two or three magnetic field sensors that provide data for a microprocessor. The correct heading relative to the compass is calculated using trigonometry.

Often, the device is a discrete component which outputs either a digital or analog signal proportional to its orientation. This signal is interpreted by a controller or microprocessor and used either internally, or sent to a display unit. The sensor uses highly calibrated internal electronics to measure the response of the device to the Earth's magnetic field.

GPS receivers using two or more antennae can now achieve 0.5° in heading accuracy and have startup times in seconds rather than hours for gyrocompass systems. Manufactured primarily for maritime applications, they can also detect pitch and roll of ships.

Specialty compasses

A standard Brunton Geo, used commonly by geologists.

Apart from navigational compasses, other specialty compasses have also been designed to accommodate specific uses. These include:

- Qibla compass, which is used by Muslims to show the direction to Mecca for prayers.
- Optical or prismatic hand-bearing compass, most often used by surveyors, but also by cave explorers, foresters, and geologists. This compasses ordinarily uses a liquid-damped capsule[84] and magnetized floating compass dial with an integral optical (direct or lensatic) or prismatic sight, often fitted with built-in photoluminescent or battery-powered illumination.[] Using the optical or prism sight, such compasses can be read with extreme accuracy when taking bearings to an object, often to fractions of a degree. Most of these compasses are designed for heavy-duty use, with high-quality needles and jeweled bearings, and many are fitted for tripod mounting for additional accuracy.[]
- Trough compasses, mounted in a rectangular box whose length was often several times its width, date back several centuries. They were used for land surveying, particularly with plane tables.

Limitations of the magnetic compass

The compass is very stable in areas close to the equator, which is far from "magnetic north". As the compass is moved closer and closer to one of the magnetic poles of the Earth, the compass becomes more sensitive to crossing its magnetic field lines. At some point close to the magnetic pole the compass will not indicate any particular direction but will begin to drift. Also, the needle starts to point up or down when getting closer to the poles, because of the so-called magnetic inclination. Cheap compasses with bad bearings may get stuck because of this and therefore indicate a wrong direction.

All magnetic devices are subject to fields other than Earth's, which is not particularly strong. Local environments may contain mineral deposits and human sources such as MRIs. Vehicles may contain ferrous metals, which may pick up their own fields. Cars may be mostly steel, and render simple compasses useless after time. While ships, submarines, and spacecraft may be built from carefully controlled materials, and later degaussed, drivers rarely take such a step.

A compass is also subject to errors when the compass is accelerated or decelerated in an airplane or automobile. Depending on which of the Earth's hemispheres the compass is located and if the force is acceleration or deceleration the compass will increase the indicated heading or decrease the indicated heading.

Another error of the mechanical compass is turning error. When one turns from a heading of east or west the compass will lag behind the turn or lead ahead of the turn. Magnetometers, and substitutes such as gyrocompasses, are more stable in such situations.

Construction of a compass

Magnetic needle

A magnetic rod is required when constructing a compass. This can be created by aligning an iron or steel rod with Earth's magnetic field and then tempering or striking it. However, this method produces only a weak magnet so other methods are preferred. For example, a magnetised rod can be created by repeatedly rubbing an iron rod with a magnetic lodestone. This magnetised rod (or magnetic needle) is then placed on a low friction surface to allow it to freely pivot to align itself with the magnetic field. It is then labeled so the user can distinguish the north-pointing

from the south-pointing end; in modern convention the north end is typically marked in some way.

Needle-and-bowl device

If a needle is rubbed on a lodestone or other magnet, the needle becomes magnetized. When it is inserted in a cork or piece of wood, and placed in a bowl of water it becomes a compass. Such devices were universally used as compass until the invention of the box-like compass with a 'dry' pivoting needle sometime around 1300.

Points of the compass

Originally, many compasses were marked only as to the direction of magnetic north, or to the four cardinal points (north, south, east, west). Later, these were divided, in China into 24, and in Europe into 32 equally spaced points around the compass card. For a table of the thirty-two points, see compass points.

Wrist compass of the Soviet Army with counterclockwise double graduation: 60° (like a watch) and 360°.

In the modern era, the 360-degree system took hold. This system is still in use today for civilian navigators. The degree system spaces 360 equidistant points located clockwise around the compass dial. In the 19th century some European nations adopted the "grad" (also called grade or gon) system instead, where a right angle is 100 grads to give a circle of 400 grads. Dividing grads into tenths to give a circle of 4000 decigrades has also been used in armies.

Most military forces have adopted the French "millieme" system. This is an approximation of a milli-radian (6283 per circle), in which the compass dial is spaced into 6400 units or "mils" for additional precision when measuring angles, laying artillery, etc. The value to the military is that one angular mil subtends approximately one metre at a distance of one kilometer. Imperial Russia used a system derived by dividing the circumference of a circle into chords of the same length as the radius. Each of these was divided into 100 spaces, giving a circle of 600. The Soviet Union divided these into tenths to give a circle of 6000 units, usually translated as "mils". This system was adopted by the former Warsaw Pact countries (Soviet Union, GDR etc.), often counterclockwise (see picture of wrist compass). This is still in use in Russia.

Compass balancing (magnetic dip)

Because the Earth's magnetic field's inclination and intensity vary at different latitudes, compasses are often balanced during manufacture so that the dial or needle will be level, eliminating needle drag which can give inaccurate readings. Most manufacturers balance their compass needles for one of five zones, ranging from zone 1, covering most of the Northern Hemisphere, to zone 5 covering Australia and the southern oceans. This individual zone balancing prevents excessive dipping of one end of the needle which can cause the compass card to stick and give false readings.[85]

Some compasses feature a special needle balancing system that will accurately indicate magnetic north regardless of the particular magnetic zone. Other magnetic compasses have a small sliding counterweight installed on the needle itself. This sliding counterweight, called a 'rider', can be used for counterbalancing the needle against the dip caused by inclination if the compass is taken to a zone with a higher or lower dip.[85]

Compass correction

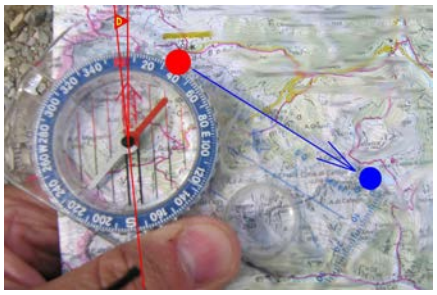
A binnacle containing a ship's steering compass, with the two iron balls which correct the effects of ferromagnetic materials. This unit is on display in a museum.

Like any magnetic device, compasses are affected by nearby ferrous materials, as well as by strong local electromagnetic forces. Compasses used for wilderness land navigation should not be used in proximity to ferrous metal objects or electromagnetic fields (car electrical systems, automobile engines, steel pitons, etc.) as that can affect their accuracy.[] Compasses are particularly difficult to use accurately in or near trucks, cars or other mechanized vehicles even when corrected for deviation by the use of built-in magnets or other devices. Large amounts of ferrous metal combined with the on-and-off electrical fields caused by the vehicle's ignition and charging systems generally result in significant compass errors.

At sea, a ship's compass must also be corrected for errors, called deviation, caused by iron and steel in its structure and equipment. The ship is *swung*, that is rotated about a fixed point while its heading is noted by alignment with fixed points on the shore. A compass deviation card is prepared so that the navigator can convert between compass and magnetic headings. The compass can be corrected in three ways. First the lubber line can be adjusted so that it is aligned with the direction in which the ship travels, then the effects of permanent magnets can be corrected for by small magnets fitted within the case of the compass. The effect of ferromagnetic materials in the compass's environment can be corrected by two iron balls mounted on either side of the compass binnacle. The coefficient $a_0$representing the error in the lubber line, while $a_1, b_1$the ferromagnetic effects and $a_2, b_2$the non-ferromagnetic componentWikipedia:Please clarify.

A similar process is used to calibrate the compass in light general aviation aircraft, with the compass deviation card often mounted permanently just above or below the magnetic compass on the instrument panel. Fluxgate electronic compasses can be calibrated automatically, and can also be programmed with the correct local compass variation so as to indicate the true heading.

Using a compass



Turning the compass scale on the map (D - the local magnetic declination).

A magnetic compass points to magnetic north pole, which is approximately 1,000 miles from the true geographic North Pole. A magnetic compass's user can determine true North by finding the magnetic north and then correcting for variation and deviation. Variation is defined as the angle between the direction of true (geographic) north and the direction of the meridian between the magnetic poles. Variation values for most of the oceans had been calculated and published by 1914.[86] Deviation refers to the response of the compass to local magnetic fields caused by the presence of iron and electric currents; one can partly compensate for these by careful location of the compass and the placement of compensating magnets under the compass itself. Mariners have long known that these measures do not completely cancel deviation; hence, they performed an additional step by measuring the compass bearing of a landmark with a known magnetic bearing. They then pointed their ship to the

next compass point and measured again, graphing their results. In this way, correction tables could be created, which would be consulted when compasses were used when traveling in those locations.

Mariners are concerned about very accurate measurements; however, casual users need not be concerned with differences between magnetic and true North. Except in areas of extreme magnetic declination variance (20 degrees or more), this is enough to protect from walking in a substantially different direction than expected over short distances, provided the terrain is fairly flat and visibility is not impaired. By carefully recording distances (time or paces) and magnetic bearings traveled, one can plot a course and return to one's starting point using the compass alone.[]

When the needle is aligned with and superimposed over the outlined orienting arrow on the bottom of the capsule, the degree figure on the compass ring at the direction-of-travel (DOT) indicator gives the magnetic bearing to the target (mountain).

Soldier using a prismatic compass to get an azimuth.

Compass navigation in conjunction with a map (*terrain association*) requires a different method. To take a map bearing or *true bearing* (a bearing taken in reference to true, not magnetic north) to a destination with a protractor compass, the edge of the compass is placed on the map so that it connects the current location with the desired destination (some sources recommend physically drawing a line). The orienting lines in the base of the compass dial are then rotated to align with actual or true north by aligning them with a marked line of longitude (or the vertical margin of the map), ignoring the compass needle entirely.[] The resulting *true bearing* or map bearing may then be read at the degree indicator or direction-of-travel (DOT) line, which may be followed as an *azimuth* (course) to the destination. If a *magnetic* north bearing or *compass bearing* is desired, the compass must be adjusted by the amount of magnetic declination before using the bearing so that both map and compass are in agreement.[] In the given example, the large mountain in the second photo was selected as the target destination on the map. Some compasses allow the scale to be adjusted to compensate for the local magnetic declination; if adjusted correctly, the compass will give the true bearing instead of the magnetic bearing.

The modern hand-held protractor compass always has an additional direction-of-travel (DOT) arrow or indicator inscribed on the baseplate. To check one's progress along a course or azimuth, or to ensure that the object in view is indeed the destination, a new compass reading may be taken to the target if visible (here, the large mountain). After pointing the DOT arrow on the baseplate at the target, the compass is oriented so that the needle is superimposed over the orienting arrow in the capsule. The resulting bearing indicated is the magnetic bearing to the target. Again, if one is using "true" or map bearings, and the compass does not have preset, pre-adjusted declination, one must additionally add or subtract magnetic declination to convert the *magnetic bearing* into a *true bearing*. The exact value of the magnetic declination is place-dependent and varies over time, though declination is frequently given on the map itself or obtainable on-line from various sites. If the hiker has been following the correct path, the compass' corrected (true) indicated bearing should closely correspond to the true bearing previously obtained from the map.

A compass should be laid down on a level surface so that the needle only rests or hangs on the bearing fused to the compass casing - if used at a tilt, the needle might touch the casing on the compass and not move freely, hence not pointing to the magnetic north accurately, giving a faulty reading. To see if the needle is well leveled, look closely at the needle, and tilt it slightly to see if the needle is swaying side to side freely and the needle is not contacting the casing of the compass. If the needle tilts to one direction, tilt the compass slightly and gently to the opposing direction until the compass needle is horizontal, lengthwise. Items to avoid around compasses are magnets of any kind and any electronics. Magnetic fields from electronics can easily disrupt the needle, avoiding it from pointing with the earth's magnetic fields, causing interference. The earth's natural magnetic forces are considerably weak, measuring at 0.5 Gauss and magnetic fields from household electronics can easily exceed it, overpowering the compass needle. Exposure to strong magnets, or magnetic interference can sometimes cause the magnetic poles of the compass needle to differ or even reverse. Avoid iron rich deposits when using a compass, for example, certain rocks which contain magnetic minerals, like Magnetite. This is often indicated by a rock with a surface which is dark and has a metallic luster, not all magnetic mineral bearing rocks have this indication. To see if a rock or an area is causing interference on a compass, get out of the area, and see if the needle on the compass moves. If it does, it means that the area or rock the compass was previously at/on is causing interference and should be avoided.

Notes

[1] Li Shu-hua, p. 176
[2] Kreutz, p. 367
[3] Needham, p. 252
[4] Li Shu-hua, p. 182f.
[5] Kreutz, p. 368
[6] http://www.uib.no/jais/v001ht/01-081-132schmidl1.htm#_ftn4
[7] Kreutz, p. 370
[8] Lane, p. 615
[9] W. H. Creak: "The History of the Liquid Compass", *The Geographical Journal*, Vol. 56, No. 3 (1920), pp. 238-239
[10] The Earth's magnetic field is approximately that of a tilted dipole. If it were exactly dipolar, the compass would point to the geomagnetic poles, which would be identical to the North Magnetic Pole and South Magnetic Pole; however, it is not, so these poles are not equivalent and the compass only points 360' off at the geomagnetic poles.
[11] Seidman, David, and Cleveland, Paul, *The Essential Wilderness Navigator*, Ragged Mountain Press (2001), ISBN 0-07-136110-3, p. 147: Since the magnetic compass is simple, durable, and requires no separate electrical power supply, it remains popular as a primary or secondary navigational aid, especially in remote areas or where power is unavailable.
[16] John B. Carlson, "Lodestone Compass: Chinese or Olmec Primacy? Multidisciplinary Analysis of an Olmec Hematite Artifact from San Lorenzo, Veracruz, Mexico", *Science*, New Series, Vol. 189, No. 4205 (5 September 1975), pp. 753-760 (1975)
[18] A. P. Guimarães, "Mexico and the early history of magnetism", *Revista Mexicana de Fisica*, Vol. 50, pp. 51-53 (2004)
[19] http://www.dartmouth.edu/~izapa/CS-MM-Chap.%203.htm
[20] http://www.gutenberg.org/cache/epub/7209/pg7209.html
[21] Needham p. 190
[22] Needham p. 18
[23] Needham p. 18 "*here the author is contrasting a fable which he did not believe with actual events he has seen with his own eyes*"
[24] Li Shu-hua, p. 180
[25] Needham p. 273-274
[26] Kreutz, p. 373
[27] Needham p. 255
[28] Needham, p. 289.
[29] Needham, p. 290
[30] http://toolserver.org/%7Edispenser/cgi-bin/dab_solver.py?page=Compass&editintro=Template:Disambiguation_needed/editintro&client=Template:Dn
[31] Zhou
[32] Ma, Appendix 2
[33] Kreutz, p. 369
[34] Needham p. 12-13 "*...that the floating fish-shaped iron leaf spread outside China as a technique, we know from the description of Muhammad al' Awfi just two hundred years later*"
[35] Kreutz, p. 368–369

[36] Lane, p. 606f.
[37] Lane, p. 608
[38] Lane, p. 608 & 610
[39] Lane, p. 608 & 613
[40] Kreutz, p. 372–373
[41] Emilie Savage-Smith (1988), "Gleanings from an Arabist's Workshop: Current Trends in the Study of Medieval Islamic Science and Medicine", *Isis* **79** (2): 246-266 [263]
[42] G. R. Tibbetts (1973), "Comparisons between Arab and Chinese Navigational Techniques", *Bulletin of the School of Oriental and African Studies* **36** (1): 97-108 [105-6]
[46] Taylor
[47] Lane, p. 616
[48] Kreutz, p. 374
[50] Frazer, Persifor, *A Convenient Device to be Applied to the Hand Compass*, Proceedings of the American Philosophical Society, Vol. 22, No. 118 (Mar., 1885), p. 216
[51] The Compass Museum, *The Bézard Compass*, Article (http://www.compassmuseum.com/hand/bezard.htm)
[52] Barnes, Scott, Churchill, James, and Jacobson, Cliff, *The Ultimate Guide to Wilderness Navigation*, Globe Pequot Press (2002), ISBN 1-58574-490-5, ISBN 978-1-58574-490-9, p. 27
[53] Barnes, p. 27
[54] Litsky, Frank, *Bjorn Kjellstrom, 84, Orienteer and Inventor of Modern Compass*, Obituaries, The New York Times, 1 September 1995
[55] Seidman, p. 68
[56] Kjellström, Björn, *19th Hole: The Readers Take Over: Orienteering*, Sports Illustrated, 3 March 1969
[57] Silva Sweden AB, *Silva Sweden AB and Silva Production AB Become One Company: History*, Press Release 28 April 2000
[58] Gubbins, David, *Encyclopedia of Geomagnetism and Paleomagnetism*, Springer Press (2007), ISBN 1-4020-3992-1, ISBN 978-1-4020-3992-8, p. 67
[59] Fanning, A.E., *Steady As She Goes: A History of the Compass Department of the Admiralty*, HMSO, Department of the Admiralty (1986), pp. 1-10
[60] Gubbins, p. 67
[61] Fanning, A.E., pp. 1-10
[62] Warner, Deborah, *Compasses and Coils: The Instrument Business of Edward S. Ritchie*, Rittenhouse, Vol. 9, No. 1 (1994), pp. 1-24
[63] Gubbins, p. 67: The use of parallel or multiple needles was by no means a new development; their use in dry-mount marine compasses was pioneered by navigation officers of the Dutch East India Company as early as 1649.
[64] Davis, Sophia, *Raising The Aerocompass In Early Twentieth-century Britain*, British Journal for the History of Science, published online by Cambridge University Press, 15 Jul 2008, pp. 1-22
[65] Colvin, Fred H., *Aircraft Mechanics Handbook: A Collection of Facts and Suggestions from Factory and Flying Field to Assist in Caring for Modern Aircraft*, McGraw-Hill Book Co. Inc. (1918), pp. 347-348
[66] The Compass Museum, Article (http://www.compassmuseum.com/wrist/wrist_1.htm#C-O): Though the *Creagh-Osborne* was offered in a wrist-mount model, it proved too bulky and heavy in this form.
[67] Hughes, Henry A., *Improvements in prismatic compasses with special reference to the Creagh-Osborne patent compass*, Transactions of The Optical Society 16, London: The Optical Society (1915), pp. 17-43: The first liquid-damped compass compact enough for pocket or pouch was the *Creagh-Osborne*, patented in 1915 in Great Britain.
[68] Hughes, Henry A., pp. 17-43
[69] Suunto Oy, *Suunto Company History*, December 2001 Article (http://www.suunto.com/suunto/Worlds/outdoor/main/outdoor_article_normal.jsp?)
[70] N. Abrahamsen: "Evidence for Church Orientation by Magnetic Compass in Twelfth-Century Denmark", *Archaeometry*, Vol. 32, No. 2 (1992), pp. 293-303 (293)
[71] N. Abrahamsen: "Evidence for Church Orientation by Magnetic Compass in Twelfth-Century Denmark", Archaeometry, Vol. 32, No. 2 (1992), pp. 293-303 (303)
[72] Ludwig and Schmidtchen, p. 62–64
[73] Ludwig and Schmidtchen, p. 64
[74] Taylor, p. 1f.
[75] *Gear Review: Kasper & Richter Alpin Compass*, OceanMountainSky.Com
[76] Nemoto & Co. Ltd., Article (http://www.nemoto.co.jp/en/products/luminova/luminova.html): In addition to ordinary phosphorescent luminous paint (zinc sulfide), brighter photoluminescent coatings of strontium aluminate or isotopes of self-luminous tritium are now being used on modern compasses.
[77] Kjernsmo, Kjetil, '[www.learn-orienteering.org/old/buying.html How to use a Compass]*, retrieved 8 April 2012*
[78] U.S. Army, *Map Reading and Land Navigation*, FM 21-26, Headquarters, Dept. of the Army, Washington, D.C. (7 May 1993), ch. 11, pp. 1-3: Any 'floating card' type compass with a straightedge or centerline axis can be used to read a map bearing by orienting the map to magnetic north using a drawn magnetic azimuth, but the process is far simpler with a protractor compass.

[79] ' Article MIL-PRF-10436N (http://landnavigation.org/Documents/Compass Mil Specs.pdf), *rev. 31 October 2003, Washington, D.C.: U.S. Dept. of Defense*

[80] Kearny, Cresson H., *Jungle Snafus...And Remedies*, Oregon Institute Press (1996), ISBN 1-884067-10-7, pp. 164-170: In 1989, one U.S. Army jungle infantry instructor reported that about 20% of the issue lensatic compasses in his company used in a single jungle exercise in Panama were ruined within three weeks by rain and humidity.

[81] Ministry of Defence, *Manual of Map Reading and Land Navigation*, HMSO Army Code 70947 (1988), ISBN 0-11-772611-7, ISBN 978-0-11-772611-6, ch. 8, sec. 26, pp. 6-7; ch. 12, sec. 39, p. 4

[83] CRC Handbook of Chemistry and Physics. page B247

[84] Kramer, Melvin G., U.S. Patent No. 4175333, *Magnetic Compass*, Riverton, Wyoming: The Brunton Company, pub. 27 November 1979: The *Brunton Pocket Transit*, which uses magnetic induction damping, is an exception.

[85] Global compasses (http://www.mapworld.co.nz/global.html), MapWorld.

[86] Wright, Monte, Most Probable Position, University Press of Kansas, Lawrence, 1972, p.7

References

- Admiralty, Great Britain (1915) *Admiralty manual of navigation, 1914*, Chapter XXV: "The Magnetic Compass (continued): the analysis and correction of the deviation", London : HMSO, 525 p.
- Aczel, Amir D. (2001) *The Riddle of the Compass: The Invention that Changed the World*, 1st Ed., New York : Harcourt, ISBN 0-15-600753-3
- Carlson, John B. (1975) "Lodestone Compass: Chinese or Olmec Primacy? (http://www.sciencemag.org/cgi/content/abstract/189/4205/753): Multidisciplinary analysis of an Olmec hematite artifact from San Lorenzo, Veracruz, Mexico", *Science*, **189** (4205 : 5 September), p. 753-760, DOI 10.1126/science.189.4205.753
- Gies, Frances and Gies, Joseph (1994) *Cathedral, Forge, and Waterwheel: Technology and Invention in the Middle Age*, New York : HarperCollins, ISBN 0-06-016590-1
- Gubbins, David, *Encyclopedia of Geomagnetism and Paleomagnetism*, Springer Press (2007), ISBN 1-4020-3992-1, ISBN 978-1-4020-3992-8
- Gurney, Alan (2004) *Compass: A Story of Exploration and Innovation*, London : Norton, ISBN 0-393-32713-2
- Johnson, G. Mark, *The Ultimate Desert Handbook*, 1st Ed., Camden, Maine: McGraw-Hill (2003), ISBN 0-07-139303-X
- King, David A. (1983). "The Astronomy of the Mamluks". *Isis* **74** (4): 531–555. doi: 10.1086/353360 (http://dx.doi.org/10.1086/353360)
- Kreutz, Barbara M. (1973) "Mediterranean Contributions to the Medieval Mariner's Compass", *Technology and Culture*, **14** (3: July), p. 367–383
- Lane, Frederic C. (1963) "The Economic Meaning of the Invention of the Compass", *The American Historical Review*, **68** (3: April), p. 605–617
- Li Shu-hua (1954) "Origine de la Boussole 11. Aimant et Boussole", *Isis*, **45** (2: July), p. 175–196
- Ludwig, Karl-Heinz and Schmidtchen, Volker (1997) *Metalle und Macht: 1000 bis 1600*, Propyläen Technikgeschichte, Berlin : Propyläen-Verl., ISBN 3-549-05633-8
- Ma, Huan (1997) *Ying-yai sheng-lan* [The overall survey of the ocean's shores (1433)], Feng, Ch'eng-chün (ed.) and Mills, J.V.G. (transl.), Bangkok : White Lotus Press, ISBN 974-8496-78-3
- Needham, Joseph (1986) *Science and civilisation in China*, Vol. 4: "Physics and physical technology", Pt. 1: "Physics", Taipei: Caves Books, originally publ. by Cambridge University Press (1962), ISBN 0-521-05802-3
- Needham, Joseph and Ronan, Colin A. (1986) *The shorter Science and civilisation in China : an abridgement of Joseph Needham's original text*, Vol. 3, Chapter 1: "Magnetism and Electricity", Cambridge University Press, ISBN 0-521-25272-5
- Seidman, David, and Cleveland, Paul, *The Essential Wilderness Navigator*, Ragged Mountain Press (2001), ISBN 0-07-136110-3
- Taylor, E.G.R. (1951) "The South-Pointing Needle", *Imago Mundi*, **8**, p. 1–7
- Williams, J.E.D. (1992) *From Sails to Satellites: the origin and development of navigational science*, Oxford University Press, ISBN 0-19-856387-6

- Wright, Monte Duane (1972) *Most Probable Position: A History of Aerial Navigation to 1941*, The University Press of Kansas, Library of Congress Catalog Card Number 72-79318
- Zhou, Daguan (2007) *The customs of Cambodia*, translated into English from the French version by Paul Pelliot of Zhou's Chinese original by J. Gilman d'Arcy Paul, Phnom Penh : Indochina Books, prev publ. by Bangkok : Siam Society (1993), ISBN 974-8298-25-6

External links

- How to Make a Compass (http://www.magnet.fsu.edu/mediacenter/slideshows/compass/index.html) Audio slideshow from the National High Magnetic Field Laboratory
- Science Friday, " *The Riddle of the Compass* (http://www.sciencefriday.com/pages/2002/May/hour2_053102.html)" (interview with Amir Aczel, first broadcast on NPR on May 31, 2002).
- Paul J. Gans, The Medieval Technology Pages: Compass (http://scholar.chem.nyu.edu/tekpages/compass.html)
- The Tides By Sir William Thomson (Lord Kelvin)
- Evening Lecture To The British Association At The Southampton Meeting on Friday, August 25, 1882 (http://zapatopi.net/kelvin/papers/the_tides.html). Refers to compass correction by Fourier series.
- Arrick Robots. Robotics.com Example implementation for digital solid-state compass. *ARobot Digital Compass App Note* (http://www.robotics.com/arobot/compass.html)
- How a tilt sensor works. David Pheifer (http://www.sensorsmag.com/articles/0500/120/main.shtml)
- The Gear Junkie (http://thegearjunkie.com/the-thumb-compass) - review of two orienteering thumb compasses
- The good compass video (http://www.odoo.tv/The-good-Compass.62.0.html?&L=1) - A video about important abilities a compass should have (narration in German)
- COMPASSIPEDIA, the great virtual Compass Museum (http://www.compassmuseum.com/) gives comprehensive information about all sorts of compasses and how to use them.
- Geography fieldwork (http://geographyfieldwork.com/UsingCompass.htm)
- Travel Island (http://www.travel-island.com/travel.outdoor.gears/how.works.compass.maps.html) (DEAD LINK)
- Compass whistles Seven types and subgroups. (http://whistlemuseum.com/2009/05/30/compass-whistles-seven-types--subgroups-a-strauss-2.aspx?ref=rss)

Sundial

A **sundial** is a device that tells the time of day by the position of the Sun. In common designs such as the horizontal sundial, the sun casts a shadow from its *style* onto a surface marked with lines indicating the hours of the day. The style is the time-telling edge of the *gnomon*, often a thin rod or a sharp, straight edge. As the sun moves across the sky, the shadow-edge aligns with different hour-lines. All sundials must be aligned with their styles parallel to the axis of the Earth's rotation to tell the correct time throughout the year. The style's angle from the horizontal will thus equal the sundial's geographical latitude.

It is common for inexpensive decorative sundials to have incorrect hour angles, which cannot be adjusted to tell correct time.[1]

SSW facing, vertical declining sundial on Moot Hall, Aldeburgh, Suffolk, England.

Ancient sundial from Marcianopolis

There are different types of sundials: Some sundials use a shadow or the edge of a shadow while others use a line or spot of light to indicate the time.

The shadow-casting object, known as a *gnomon*, may be a thin rod, or other object with a sharp tip or a straight edge. Sundials employ many types of gnomon. The gnomon may be fixed or moved according to the season. It may be oriented vertically, horizontally, aligned with the Earth's axis, or oriented in an altogether different direction determined by mathematics.

A horizontal sundial in the Kadriorg Park in Tallinn, Estonia

With sundials using light to indicate time, a line of light may be formed by allowing the sun's rays through a thin slit or focusing them through a cylindrical lens. A spot of light may be formed by allowing the sun's rays to pass through a small hole or by reflecting them from a small circular mirror.

Sundials also may use many types of surfaces to receive the light or shadow. Planes are the most common surface, but partial spheres, cylinders, cones and other shapes have been used for greater accuracy or beauty.

Sundials differ in their portability and their need for orientation. The installation of many dials requires knowing the local latitude, the precise vertical direction (e.g., by a level or plumb-bob), and the direction to true North. Portable dials are self-aligning; for example, it may have two dials that operate on different principles, such as a horizontal and analemmatic dial, mounted together on one plate. In these designs, their times agree only when the plate is aligned properly.

Sundials indicate the local solar time, unless corrected for some other time. To obtain the official clock time, three types of corrections need to be made.

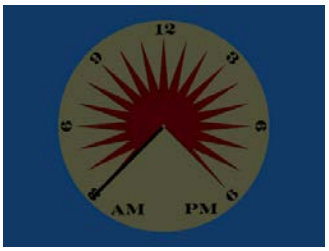
First, the orbit of the Earth is not perfectly circular and its rotational axis not perfectly perpendicular to its orbit. The sundial's indicated solar time thus varies from clock time by small amounts that change throughout the year. This correction — which may be as great as 15 minutes — is described by the equation of time. A sophisticated sundial, with a curved style or hour lines, may incorporate this correction. Often instead, simpler sundials are used, with a small plaque that gives the offsets at various times of the year.

Second, the solar time must be corrected for the longitude of the sundial relative to the longitude of the official time zone. For example, a sundial located *west* of Greenwich, England but within the same time-zone, shows an *earlier* time than the official time. It will show "noon" after the official noon has passed, since the sun passes overhead later. This correction is often made by rotating the hour-lines by an angle equal to the difference in longitudes.

Last, to adjust for daylight saving time, the sundial must shift the time away from solar time by some amount, usually an hour. This correction may be made in the adjustment plaque, or by numbering the hour-lines with two sets of numbers.

Apparent motion of the Sun

The principles of sundials are understood most easily from the Sun's apparent motion. The Earth rotates on its axis, and revolves in an elliptical orbit around the Sun. An excellent approximation assumes that the Sun revolves around a stationary Earth on the celestial sphere, which rotates every 24 hours about its celestial axis. The celestial axis is the line connecting the celestial poles. Since the celestial axis is aligned with the axis about which the Earth rotates, the angle of the axis with the local horizontal is the local geographical latitude.



Top view of an equatorial sundial. The hour lines are spaced equally about the circle, and the shadow of the gnomon (a thin cylindrical rod) rotates uniformly. The height of the gnomon is 5/12 the outer radius of the dial. This animation depicts the motion of the shadow from 3 a.m. to 9 p.m. (not accounting for Daylight Saving Time) on or around Solstice, when the sun is at its highest declination (roughly 23.5°). Sunrise and sunset occur at 3am and 9pm, respectively, on that day at geographical latitudes near 57.05°, roughly the latitude of Aberdeen, Scotland or Sitka, Alaska.

Unlike the fixed stars, the Sun changes its position on the celestial sphere, being at a positive declination in summer, at a negative declination in winter, and having exactly zero declination (i.e., being on the celestial equator) at the equinoxes. The Sun's celestial longitude also varies, changing by one complete revolution per year. The path of the Sun on the celestial sphere is called the ecliptic. The ecliptic passes through the twelve constellations of the zodiac in the course of a year.

Sundial in Singapore Botanic Gardens. The fact that Singapore is located almost at the equator is reflected in its design.

This model of the Sun's motion helps to understand sundials. If the shadow-casting gnomon is aligned with the celestial poles, its shadow will revolve at a constant rate, and this rotation will not change with the seasons. This is the most common design. In such cases, the same hour lines may be used throughout the year. The hour-lines will be spaced uniformly if the surface receiving the shadow is either perpendicular (as in the equatorial sundial) or circular about the gnomon (as in the armillary sphere).

In other cases, the hour-lines are not spaced evenly, even though the shadow rotates uniformly. If the gnomon is *not* aligned with the celestial poles, even its shadow will not rotate uniformly, and the hour lines must be corrected accordingly. The rays of light that graze the tip of a gnomon, or which pass through a small hole, or reflect from a small mirror, trace out a cone aligned with the celestial poles. The corresponding light-spot or shadow-tip, if it falls onto a flat surface, will trace out a conic section, such as a hyperbola, ellipse or (at the North or South Poles) a circle.

This conic section is the intersection of the cone of light rays with the flat surface. This cone and its conic section change with the seasons, as the Sun's declination changes; hence, sundials that follow the motion of such light-spots or shadow-tips often have different hour-lines for different times of the year. This is seen in shepherd's dials, sundial

rings, and vertical gnomons such as obelisks. Alternatively, sundials may change the angle and/or position of the gnomon relative to the hour lines, as in the analemmatic dial or the Lambert dial.

History

The earliest sundials known from the archaeological record are the obelisks (3500 BC) and shadow clocks (1500 BC) from ancient Egyptian astronomy and Babylonian astronomy. Presumably, humans were telling time from shadow-lengths at an even earlier date, but this is hard to verify. In roughly 700 BC, the Old Testament describes a sundial — the "dial of Ahaz" mentioned in Isaiah 38:8 [2] and II Kings 20:9 [3]. The Roman writer Vitruvius lists dials and shadow clocks known at that time. Italian astronomer Giovanni Padovani published a treatise on the sundial in 1570, in which he included instructions for the manufacture and laying out of mural (vertical) and horizontal sundials. Giuseppe Biancani's *Constructio instrumenti ad horologia solaria* (ca. 1620) discusses how to make a perfect sundial. They have been commonly used since the 16th century.

Terminology

In general, sundials indicate the time by casting a shadow or throwing light onto a surface known as a *dial face* or *dial plate*. Although usually a flat plane, the dial face may also be the inner or outer surface of a sphere, cylinder, cone, helix, and various other shapes.

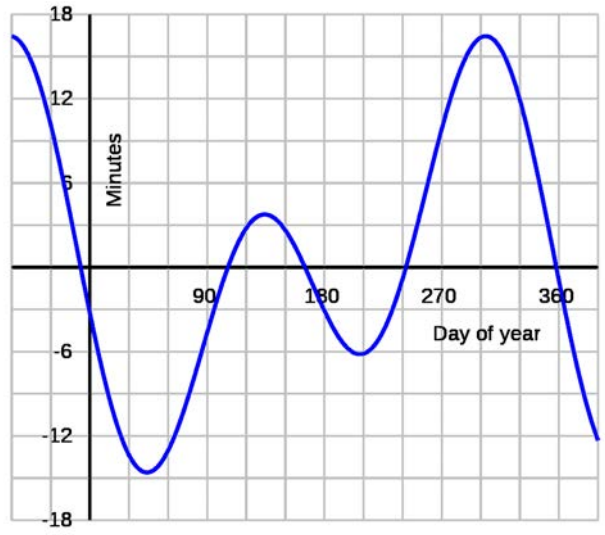
The time is indicated where a shadow or light falls on the dial face, which is usually inscribed with hour lines. Although usually straight, these hour lines may also be curved, depending on the design of the sundial (see below). In some designs, it is possible to determine the date of the year, or it may be required to know the date to find the correct time. In such cases, there may be multiple sets of hour lines for different months, or there may be mechanisms for setting/calculating the month. In addition to the hour lines, the dial face may offer other data—such as the horizon, the equator and the tropics—which are referred to collectively as the dial furniture.

The entire object that casts a shadow or light onto the dial face is known as the sundial's *gnomon*.[] However, it is usually only an edge of the gnomon (or another linear feature) that casts the shadow used to determine the time; this linear feature is known as the sundial's *style*. The style is usually aligned parallel to the axis of the celestial sphere, and therefore is aligned with the local geographical meridian. In some sundial designs, only a point-like feature, such as the tip of the style, is used to determine the time and date; this point-like feature is known as the sundial's *nodus*.[][4] Some sundials use both a style and a nodus to determine the time and date.

The gnomon is usually fixed relative to the dial face, but not always; in some designs such as the analemmatic sundial, the style is moved according to the month. If the style is fixed, the line on the dial plate perpendicularly beneath the style is called the *substyle*,[] meaning "below the style". The angle the style makes with the plane of the dial plate is called the substyle height, an unusual use of the word *height* to mean an *angle*. On many wall dials, the substyle is not the same as the noon line (see below). The angle on the dial plate between the noon line and the substyle is called the *substyle distance*, an unusual use of the word *distance* to mean an *angle*.

By tradition, many sundials have a Motto. The motto is usually in the form of an epigram: sometimes sombre reflections on the passing of time and the brevity of life, but equally often humorous witticisms of the dial maker.[5] [6]

A dial is said to be *equiangular* if its hour-lines are straight and spaced equally. Most equiangular sundials have a fixed gnomon style aligned with the Earth's rotational axis, as well as a shadow-receiving surface that is symmetrical about that axis; examples include the equatorial dial, the equatorial bow, the armillary sphere, the cylindrical dial and the conical dial. However, other designs are equiangular, such as the Lambert dial, a version of the analemmatic dial with a moveable style.



The Equation of Time

Sundials in the Southern Hemisphere

Southern-hemisphere sundial in Perth, Australia. Magnify to see that the hour marks run anticlockwise. Note graph of Equation of Time, needed to correct sundial readings.

A sundial at a particular latitude in one hemisphere must be reversed for use at the opposite latitude in the other hemisphere.[] A vertical direct south sundial in the Northern Hemisphere becomes a vertical direct north sundial in the Southern Hemisphere. To position a horizontal sundial correctly, one has to find true North or South. The same process can be used to do both.[] The gnomon, set to the correct latitude, has to point to the true South in the Southern hemisphere as in the Northern Hemisphere it has to point to the true North.[] Also the hour numbers go in opposite directions, so on a horizontal dial they run anti-clockwise rather than clockwise.[7]

Sundials which are designed to be used with their plates horizontal in one hemisphere can be used with their plates vertical at the complementary latitude in the other hemisphere. For example, the illustrated sundial in Perth. Australia, which is at latitude 32 degrees South, would function properly if it were mounted on a south-facing vertical wall at latitude 58 (i.e. 90-32) degrees North, which is slightly further North than Perth, Scotland. The surface of the wall in Scotland would be parallel with the horizontal ground in Australia (ignoring the difference of longitude), so the sundial would work identically on both surfaces.

Sundials are used much less in the Southern Hemisphere than the Northern. One reason for this is the seasonal asymmetry of the Equation of Time. (See also **below**.) From early November to mid-February, during the Southern Hemisphere's summer, a sundial loses about half an hour relative to a clock. This adds to the difficulty of using it as a timepiece. The change during the northern summer is only about one-third as great, and is often ignored without causing much error. Since sundials are mainly used during the summer months, they are therefore better suited to the Northern Hemisphere.

Sundials with fixed axial gnomon

The most commonly observed sundials are those in which the shadow-casting style is fixed in position and aligned with the Earth's rotational axis, being oriented with true North and South, and making an angle with the horizontal equal to the geographical latitude. This axis is aligned with the celestial poles, which is closely, but not perfectly, aligned with the (present) pole star Polaris. For illustration, the celestial axis points vertically at the true North Pole, where it points horizontally on the equator. At Jaipur, a famous location for sundials, gnomons are raised 26°55" above horizontal, reflecting the local latitude.

On any given day, the Sun appears to rotate uniformly about this axis, at about 15° per hour, making a full circuit (360°) in 24 hours. A linear gnomon aligned with this axis will cast a sheet of shadow (a half-plane) that, falling opposite to the Sun, likewise rotates about the celestial axis at 15° per hour. The shadow is seen by falling on a receiving surface that is usually flat, but which may be spherical, cylindrical, conical or of other shapes. If the shadow falls on a surface that is symmetrical about the celestial axis (as in an armillary sphere, or an equatorial dial), the surface-shadow likewise moves uniformly; the hour-lines on the sundial are equally spaced. However, if the receiving surface is not symmetrical (as in most horizontal sundials), the surface shadow generally moves non-uniformly and the hour-lines are not equally spaced; one exception is the Lambert dial described below.

Some types of sundials are designed with a fixed gnomon that is not aligned with the celestial poles, such as a vertical obelisk. Such sundials are covered below under the section, "Nodus-based sundials".

Equatorial sundials

The distinguishing characteristic of the *equatorial dial* (also called the *equinoctial dial*) is the planar surface that receives the shadow, which is exactly perpendicular to the gnomon's style.[9] [10] [11] This plane is called equatorial, because it is parallel to the equator of the Earth and of the celestial sphere. If the gnomon is fixed and aligned with the Earth's rotational axis, the sun's apparent rotation about the Earth casts a uniformly rotating sheet of shadow from the gnomon; this produces a uniformly rotating line of shadow on the equatorial plane. Since the sun rotates 360° in 24 hours, the hour-lines on an equatorial dial are all spaced 15° apart (360/24). The uniformity of their spacing makes this type of sundial easy to construct. Both sides of the equatorial dial must be marked, since the shadow will be cast from below in winter and from above in summer. Near the equinoxes in spring and autumn, the sun moves on a circle that is nearly the same as the equatorial plane; hence, no clear shadow is produced on the equatorial dial at those times of year, a drawback of the design.

An equatorial sundial in the Forbidden City, Beijing. 39°54′57″N 116°23′25″E [8] The gnomon points true North and its angle with horizontal equals the local latitude. Closer inspection of the full-size image reveals the "spider-web" of date rings and hour-lines.

A *nodus* is sometimes added to equatorial sundials, which allows the sundial to tell the time of year. On any given day, the shadow of the nodus moves on a circle on the equatorial plane, and the radius of the circle measures the declination of the sun. The ends of the gnomon bar may be used as the nodus, or some feature along its length. An ancient variant of the equatorial sundial has only a nodus (no style) and the concentric circular hour-lines are arranged to resemble a spider-web.[12]

Horizontal sundials

Horizontal sundial in Minnesota. June 17, 2007 at 12:21. 44°51′39.3″N, 93°36′58.4″W

In the *horizontal sundial* (also called a *garden sundial*), the plane that receives the shadow is aligned horizontally, rather than being perpendicular to the style as in the equatorial dial.[13] [14] [15] Hence, the line of shadow does not rotate uniformly on the dial face; rather, the hour lines are spaced according to the rule [16] [17]

$$\tan\theta = \sin\lambda \tan(15^\circ \times t)$$

where λ is the sundial's geographical latitude (and the angle the style makes with horizontal), θ is the angle between a given hour-line and the noon hour-line (which always points towards true North) on the plane, and *t* is the number of hours before or after noon. For example, the angle θ of the 3pm hour-line would equal the arctangent of sin(λ), since tan(45°) = 1. When λ equals 90° (at the North Pole), the horizontal sundial becomes an equatorial sundial; the style points straight up (vertically), and the horizontal plane is aligned with the equatorial place; the hour-line formula becomes θ = 15° × t, as for an equatorial dial. A horizontal sundial at the Earth's equator, where λ equals 0°, would require a (raised) horizontal style and would be an example of a polar sundial (see below).

The chief advantages of the horizontal sundial are that it is easy to read, and the sun lights the face throughout the year. All the hour-lines intersect at the point where the gnomon's style crosses the horizontal plane. Since the style is aligned with the Earth's rotational axis, the style points true North and its angle with the horizontal equals the sundial's geographical latitude λ. A sundial designed for one latitude can be used in another latitude, provided that the sundial is tilted upwards or downwards by an angle equal to the difference in latitude. For example, a sundial designed for a latitude of 40° can be used at a latitude of 45°, if the sundial plane is tilted upwards by 5°, thus aligning the style with the Earth's rotational axis. Many ornamental sundials are designed to be used at 45 degrees north. A sundial designed for one latitude can be adjusted for use at another latitude by tilting its base so that its style, or gnomon, is parallel to the Earth's axis of rotation and pointing in the direction of the north celestial pole in the northern hemisphere, or the south celestial pole in the southern hemisphere. Some mass-produced garden sundials fail to correctly calculate the *hourlines* so can never be corrected. A local standard time zone is nominally 15 degrees wide, but may be modified to follow geographic or political boundaries. A sundial can be rotated around its style (which must remain pointed at the celestial pole) to adjust to the local time zone. In most cases, a rotation in the range of 7.5 degrees east to 23 degrees west suffices. This will introduce error in sundials that do not have equal hour angles. To correct for daylight saving time, a face needs two sets of numerals or a correction table. An informal standard is to have numerals in hot colors for summer, and in cool colors for winter.

Vertical sundials

Two vertical dials at Houghton Hall Norfolk UK 52°49′39″N 0°39′27″E [18]. The left and right dials face South and East, respectively. Both styles are parallel, their angle to the horizontal equaling the latitude. The East-facing dial is a polar dial with parallel hour-lines, the dial-face being parallel to the style.

In the common *vertical dial*, the shadow-receiving plane is aligned vertically; as usual, the gnomon's style is aligned with the Earth's axis of rotation.[9] [19] [20] As in the horizontal dial, the line of shadow does not move uniformly on the face; the sundial is not *equiangular*. If the face of the vertical dial points directly south, the angle of the hour-lines is instead described by the formula[21] [22]

$$\tan\theta = \cos\lambda \tan(15^\circ \times t)$$

where λ is the sundial's geographical latitude, θ is the angle between a given hour-line and the noon hour-line (which always points due north) on the plane, and *t* is the number of hours before or after noon. For example, the angle θ of the 3pm hour-line would equal the arctangent of cos(λ), since tan(45°) = 1. Interestingly, the shadow moves *counter-clockwise* on a South-facing vertical dial, whereas it runs clockwise on horizontal and equatorial dials.

Dials with faces perpendicular to the ground and which face directly South, North, East, or West are called *vertical direct dials*.[23] [24] It is widely believed, and stated in respectable publications, that a vertical dial cannot receive more than twelve hours of sunlight a day, no matter how many hours of daylight there are.[25] However, there is an exception. Vertical sundials in the tropics which face the nearer pole (e.g. north facing in the zone between the Equator and the Tropic of Cancer), can actually receive sunlight for more than 12 hours from sunrise to sunset for a short period around the time of the summer solstice. For example, at latitude 20 degrees North, on June 21, the sun shines on a north-facing vertical wall for 13 hours, 21 minutes.[26] Vertical sundials which do *not* face directly South (in the northern hemisphere), may receive significantly less than twelve hours of sunlight per day, depending on the direction they do face, and on the time of year. For example, a vertical dial that faces due East can tell time only in the morning hours; in the afternoon, the sun does not shine on its face. Vertical dials that face due East or West are *polar dials*, which will be described below. Vertical dials that face North are uncommon, because they tell time only during the spring and summer, and do not show the midday hours except in tropical latitudes (and even there, only around midsummer). For non-direct vertical dials — those that face in non-cardinal directions — the mathematics of arranging the style and the hour-lines becomes more complicated; it may be easier to mark the hour lines by observation, but the placement of the style, at least, must be calculated first; such dials are said to be *declining dials*.[27] [28] [29]

"Double" sundials in Nové Město nad Metují, Czech Republic; the observer is facing almost due north.

Vertical dials are commonly mounted on the walls of buildings, such as town-halls, cupolas and church-towers, where they are easy to see from far away. In some cases, vertical dials are placed on all four sides of a rectangular tower, providing the time throughout the day. The face may be painted on the wall, or displayed in inlaid stone; the gnomon is often a single metal bar, or a tripod of metal bars for rigidity. If the wall of the building faces *toward* the South, but does not face due South, the gnomon will not lie along the noon line, and the hour lines must be corrected. Since the gnomon's style must be parallel to the Earth's axis, it always "points" true North and its angle with the horizontal will equal the sundial's geographical latitude; on a direct south dial, its angle with the vertical face of the dial will equal the colatitude, or 90° minus the latitude.[30]

Pocket sundials

This portable folding German sundial has a string gnomon (pointer), adjustable for accuracy at any latitude. As shadows fall across the sundial, the smaller dials show Italian and Babylonian hours. The dial also indicates the length of the day and the position of the sun in the zodiac.

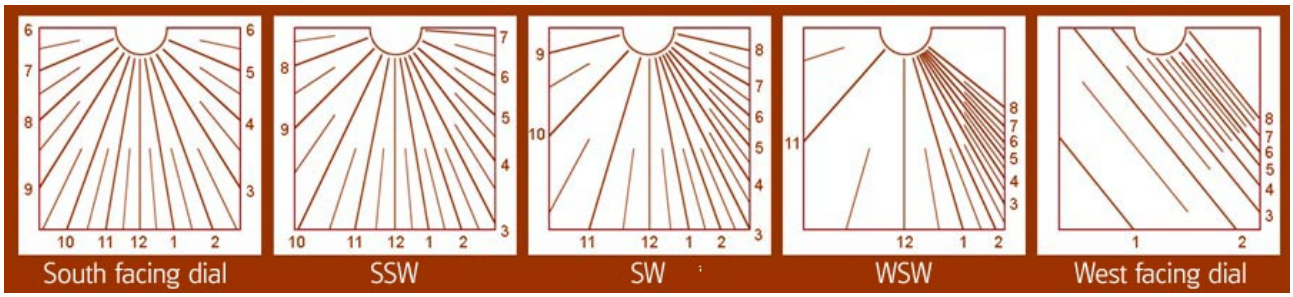
Polar dials

In *polar dials*, the shadow-receiving plane is aligned *parallel* to the gnomon-style.[31] Thus, the shadow slides sideways over the surface, moving perpendicularly to itself as the sun rotates about the style. As with the gnomon, the hour-lines are all aligned with the Earth's rotational axis. When the sun's rays are nearly parallel to the plane, the shadow moves very quickly and the hour lines are spaced far apart. The direct East- and West-facing dials are examples of a polar dial. However, the face of a polar dial need not be vertical; it need only be parallel to the gnomon. Thus, a plane inclined at the angle of latitude (relative to horizontal) under the similarly inclined gnomon will be a polar dial. The perpendicular spacing *X* of the hour-lines in the plane is described by the formula

$$X = H \tan(15^\circ \times t)$$

where *H* is the height of the style above the plane, and *t* is the time (in hours) before or after the center-time for the polar dial. The center time is the time when the style's shadow falls directly down on the plane; for an East-facing dial, the center time will be 6am, for a West-facing dial, this will be 6pm, and for the inclined dial described above, it will be noon. When *t* approaches ±6 hours away from the center time, the spacing *X* diverges to +∞; this occurs when the sun's rays become parallel to the plane.

Vertical declining dials



Effect of declining on a sundial's hour-lines. A vertical dial, at a latitude of 51° N, designed to face due South (far left) shows all the hours from 6am to 6pm, and has converging hour-lines symmetrical about the noon hour-line. By contrast, a West-facing dial (far right) is polar, with parallel hour lines, and shows only hours after noon. At the intermediate orientations of South-Southwest, Southwest, and West-Southwest, the hour lines are asymmetrical about noon, with the morning hour-lines ever more widely spaced.

A *declining dial* is any non-horizontal, planar dial that does not face in a cardinal direction, such as (true) North, South, East or West.[32] As usual, the gnomon's style is aligned with the Earth's rotational axis, but the hour-lines are not symmetrical about the noon hour-line. For a vertical dial, the angle θ between the noon hour-line and another hour-line is given by the formula[33]

$$\tan\theta = \frac{\cos\lambda}{\sin\eta\sin\lambda + \cos\eta\cot(15^\circ \times t)}$$

where λ is the sundial's geographical latitude, *t* is the time before or after noon, and η is the angle of declination from true South. When such a dial faces South (η=0°), this formula reduces to the formula given above, tan θ = cos λ tan(15° × *t*).

When a sundial is not aligned with a cardinal direction, the substyle of its gnomon is not aligned with the noon hour-line. The angle β between the substyle and the noon hour-line is given by the formula[33]

$$\tan\beta = \sin\eta\cot\lambda.$$

If a vertical sundial faces true South or North (η=0° or 180°, respectively), the correction β=0° and the substyle is aligned with the noon hour-line.

The height of the gnomon, γ (that is the angle the style makes to the plate) is

$$\sin\gamma = \cos\eta\cos\lambda.$$

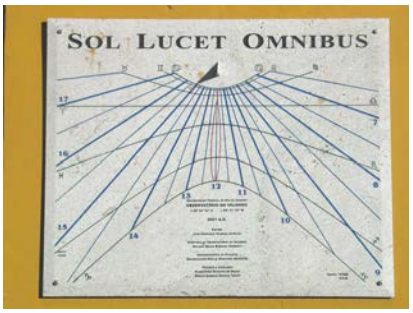
[34]

Reclining dials

The sundials described above have gnomons that are aligned with the Earth's rotational axis and cast their shadow onto a plane. If the plane is neither vertical nor horizontal nor equatorial, the sundial is said to be *reclining* or *inclining*.[35] Such a sundial might be located on a South-facing roof, for example. The hour-lines for such a sundial can be calculated by slightly correcting the horizontal formula above[36]

$$\tan\theta = \sin(\lambda+\chi)\tan(15^\circ\times t)$$

where χ is the desired angle of reclining, λ is the sundial's geographical latitude, θ is the angle between a given hour-line and the noon hour-line (which always points due north) on the plane, and *t* is the number of hours before or after noon. For example, the angle θ of the 3pm hour-line would equal the arctangent of sin(λ+χ), since tan(45°) = 1. When χ equals 90° (in other words, a South-facing vertical dial), we obtain the vertical formula above, since sin(λ+90°) = cos(λ).



Vertical reclining dial in the Southern Hemisphere, facing due north, with hyperbolic declination lines and hour lines. Ordinary vertical sundial at this latitude (between tropics) could not produce a declination line for the summer solstice.

Some authors use a more specific nomenclature to describe the orientation of the shadow-receiving plane. If the plane's face points downwards towards the ground, it is said to be *proclining* or *inclining*, whereas a dial is said to be *reclining* when the dial face is pointing away from the ground.

Reclining-declining dials

Some sundials both decline and recline, in that their shadow-receiving plane is not oriented with a cardinal direction (such as true North) and is neither horizontal nor vertical nor equatorial. For example, such a sundial might be found on a roof that was not oriented in a cardinal direction. The formulae describing the spacing of the hour-lines on such dials are rather complicated.[37] The angle θ between the noon hour-line and another hour-line has two components $\theta = \theta_1 + \theta_2$, described by the formulae[38]

$$\tan\theta_1 = \tan\eta\cos\chi$$

$$\tan\theta_2 = \frac{\cos\chi\cos\eta\sin\lambda + \sin\chi\cos\lambda - \cos\chi\sin\eta\cot(15^\circ\times t)}{\sin\eta\sin\lambda + \cos\eta\cot(15^\circ\times t)}$$

where λ is the sundial's geographical latitude, *t* is the time before or after noon, and χ and η are the angles of inclination and declination, respectively.

As in the simpler declining dial, the gnomon-substyle is not aligned with the noon hour-line.[39] The general formula for the angle β between the substyle and the noon-line is given by[40]

$$\tan\beta = \sin\chi\sin\eta\frac{\tan\lambda\cos\chi + \sin\chi\cos\eta}{\cos\chi - \tan\lambda\cos\eta\sin\chi}.$$

Spherical sundials

The surface receiving the shadow need not be a plane, but can have any shape, provided that the sundial maker is willing to mark the hour-lines. If the style is aligned with the Earth's rotational axis, a spherical shape is convenient since the hour-lines are equally spaced, as they are on the equatorial dial above; the sundial is *equiangular*. This is the principle behind the armillary sphere and the equatorial bow sundial.[42] [43] [44] However, some equiangular sundials — such as the Lambert dial described below — are based on other principles.

In the *equatorial bow sundial*, the gnomon is a bar, slot or stretched wire parallel to the celestial axis. The face is a semicircle (corresponding to the equator of the sphere, with markings on the inner surface. This pattern, built a couple of meters wide out of temperature-invariant steel invar, was used to keep the trains running on time in France before World War I.[45]

Among the most precise sundials ever made are two equatorial bows constructed of marble found in Yantra mandir.[46] [47] This collection of sundials and other astronomical instruments was built by Maharaja Jai Singh II at his then-new capital of Jaipur, India between 1727 and 1733. The larger equatorial bow is called the *Samrat Yantra* (The Supreme Instrument); standing at 27 meters, its shadow moves visibly at 1 mm per second, or roughly a hand's breadth (6 cm) every minute.

Equatorial bow sundial in Hasselt, Flanders in Belgium 50°55′47″N 5°20′31″E [41]. The rays pass through the narrow slot, forming a uniformly rotating sheet of light that falls on the circular bow. The hour-lines are equally spaced; in this image, the local solar time is roughly 15:00 hours (3 pm). On September 10, a small ball, welded into the slot casts a shadow on centre of the hour band.

Cylindrical, conical, and other non-planar sundials

Precision sundial in Bütgenbach, Belgium.
(Precision = ±30 seconds)
50°25′23″N 6°12′06″E [48]
(Google Earth) [49]

Other non-planar surfaces may be used to receive the shadow of the gnomon. For example, the gnomon may be aligned with the celestial poles and located also along the symmetry axis of a cone or a cylinder. Due to the symmetry, the hour lines on such surfaces will be equally spaced, as on an equatorial dial or an armillary sphere. The conical dial is very old, and was the basis for one type of *chalice* sundial; the style was a vertical pin within a conical goblet, within which were inscribed the hour lines.

As an elegant alternative, the gnomon may be located on the circumference of a cylinder or sphere, rather than at its center of symmetry. In that case, the hour lines are again spaced equally, but at *double* the usual angle, due to the geometrical inscribed angle theorem. This is the basis of some modern sundials, but it was also used in ancient times; in one type, the edges of a half-cylindrical gnomon served as the styles.[50]

Just as the armillary sphere is largely open for easy viewing of the dial, such non-planar surfaces need not be complete. For example, a cylindrical dial could be rendered as a helical ribbon-like surface, with a thin gnomon located either along its center or at its periphery.

Adjustments to calculate clock time from a sundial reading

The most common reason for a sundial to differ greatly from clock time is that the sundial has not been oriented correctly or its hour lines have not been drawn correctly. For example, most commercial sundials are designed as *horizontal sundials* as described above. To be accurate, such a sundial must have been designed for the local geographical latitude and its style must be parallel to the Earth's rotational axis; the style must be aligned with true North and its *height* (its angle with the horizontal) must equal the local latitude. To adjust the style height, the sundial can often be tilted slightly "up" or "down" while maintaining the style's north-south alignment.[51]

Summer (daylight saving) time correction

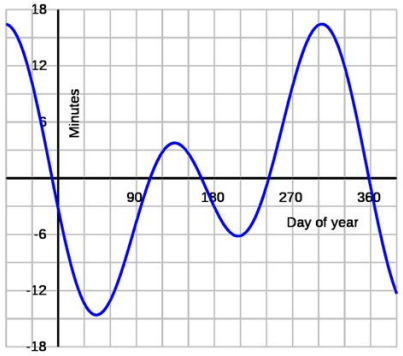
Some areas of the world practice daylight saving time, which shifts the official time, usually by one hour. This shift must be added to the sundial's time to make it agree with the official time.

Time-zone (longitude) correction

A standard time zone covers roughly 15° of longitude, so any point within that zone which is not on the reference longitude (generally a multiple of 15°) will experience a difference from standard time equal to 4 minutes of time per degree. For illustration, sunsets and sunrises are at a much later "official" time at the western edge of a time-zone, compared to sunrise and sunset times at the eastern edge. If a sundial is located at, say, a longitude 5° west of the reference longitude, its time will read 20 minutes slow, since the sun appears to revolve around the Earth at 15° per hour. This is a constant correction throughout the year. For equiangular dials such as equatorial, spherical or Lambert dials, this correction can be made by rotating the dial surface by an angle equalling the difference in longitude, without changing the gnomon position or orientation. However, this method does not work for other dials, such as a horizontal dial; the correction must be applied by the viewer.

Equation of time correction

Although the Sun appears to rotate nearly uniformly about the Earth, it is not perfectly uniform, due to the ellipticity of the Earth's orbit (the fact that the Earth's orbit about the Sun is not perfectly circular) and the tilt (obliquity) of the Earth's rotational axis relative to the plane of its orbit. Therefore, sundials time varies from standard clock time. On four days of the year, the correction is effectively zero, but on others, it can be as much as a quarter-hour early or late. The amount of correction is described by the equation of time. This correction is *universal*; it does not depend on the local latitude of the sundial. It does, however, change over long periods of time, centuries or more,[52] because of slow variations in the Earth's orbital and rotational motions. Therefore, tables and graphs of the equation of time that were made centuries ago are now significantly incorrect. The reading of an old sundial should be corrected by applying the present-day equation of time, not one from the period when the dial was made.

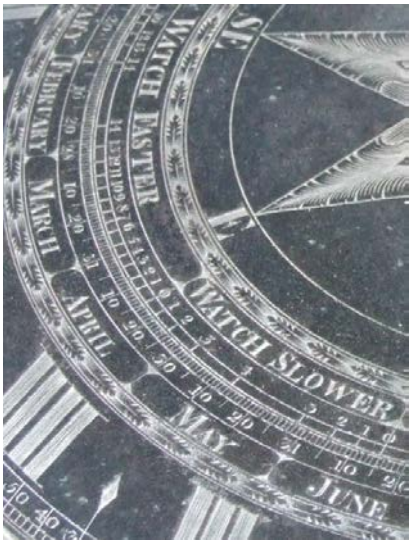


The Equation of Time - above the axis the sundial will appear *fast*, and below the sundial will appear *slow*, relative to a clock showing local mean time.

In some sundials, the equation of time correction is provided as a plaque affixed to the sundial. In more sophisticated sundials, however, the equation can be incorporated automatically. For example, some equatorial bow sundials are supplied with a small wheel that sets the

time of year; this wheel in turn rotates the equatorial bow, offsetting its time measurement. In other cases, the hour lines may be curved, or the equatorial bow may be shaped like a vase, which exploits the changing altitude of the sun over the year to effect the proper offset in time.[53] A *heliochronometer* is a precision sundial first devised in about 1763 by Philipp Hahn and improved by Abbé Guyoux in about 1827.[] It corrects apparent solar time to mean solar time or another standard time. Heliochronometers usually indicate the minutes to within 1 minute of Universal Time.

An analemma may be added to many types of sundials to correct apparent solar time to mean solar time or another standard time. These usually have hour lines shaped like "figure eights" (analemmas) according to the equation of time. This compensates for the slight eccentricity in the Earth's orbit and the tilt of the Earth's axis that causes up to a 15 minute variation from mean solar time. This is a type of dial furniture seen on more complicated horizontal and vertical dials.



The Whitehurst & Son sundial made in 1812, with a circular scale showing the equation of time correction. This is now on display in the Derby Museum.

Prior to the invention of accurate clocks, in the mid-17th Century, sundials were the only timepieces in common use, and were considered to tell the "right" time. The Equation of Time was not used. After the invention of good clocks, sundials were still considered to be correct, and clocks usually incorrect. The Equation of Time was used in the opposite direction from today, to apply a correction to the time shown by a clock to make it agree with sundial time, Some elaborate "Equation clocks", such as one made by Joseph Williamson in 1720, incorporated mechanisms to do this correction automatically. (Williamson's clock may have been the first-ever device to use a differential gear.) Only after about 1800 was uncorrected clock time considered to be "right", and sundial time usually "wrong", so the Equation of Time became used as it is today.

Movable-gnomon sundials

In addition to the sundials have a gnomon that is designed to be moved over the course of the year. In other words, the position of the gnomon relative to the center of the hour lines can vary. The advantage of such dials is that the gnomon need not be aligned with the celestial poles and may even be perfectly vertical (the analemmatic dial). A second advantage is that such dials, when combined with a fixed-gnomon sundial, allow the user to determine true North with no other aid; the two sundials are correctly aligned if and only if the time on the two sundials agrees. This is a useful property for portable sundials.

Universal equinoctial ring dial

Universal ring dial. The dial is suspended from the cord shown in the upper left; the suspension point on the vertical meridian ring can be changed to match the local latitude. The center bar is twisted until a sunray passes through the small hole and falls on the horizontal equatorial ring.

A *universal equinoctial ring dial* (sometimes called a *ring dial* for brevity, although the term is ambiguous) is a portable version of an armillary sundial,[54] or was inspired by the mariner's astrolabe.[55] It was likely invented by William Oughtred around 1600 and became common throughout Europe.[56]

In its simplest form, the style is a thin slit that allows the sun's rays to fall on the hour-lines of an equatorial ring. As usual, the style is aligned with the Earth's axis; to do this, the user may orient the dial towards true North and suspend the ring dial vertically from the appropriate point on the meridian ring. Such dials may be made self-aligning with the addition of a more complicated central bar, instead of a simple slit-style. These bars are sometimes an addition to a set of Gemma's rings. This bar could pivot about its end points and held a perforated slider that was positioned to the month and day according to a scale scribed on the bar. The time was determined by rotating the bar towards the sun so that the light shining through the hole fell on the equatorial ring. This forced the user to rotate the instrument, which had the effect of aligning the instrument's vertical ring with the meridian.

When not in use, the equatorial and meridian rings can be folded together into a small disk.

In 1610, Edward Wright created the **sea ring**, which mounted a universal ring dial over a magnetic compass. This permitted mariners to determine the time and magnetic variation in a single step.[57]

Analemmatic sundials

Analemmatic sundials are a type of horizontal sundial that has a vertical gnomon and hour markers positioned in an elliptical pattern. There are no hour lines on the dial and the time of day is read on the ellipse. The gnomon is not fixed and must change position daily to accurately indicate time of day. Analemmatic sundials are sometimes designed with a human as the gnomon. Human gnomon analemmatic sundials are not practical at lower latitudes where a human shadow is quite short during the summer months. A 66 inch tall person casts a 4 inch shadow at 27 deg latitude on the summer solstice. [58]

Analemmatic sundial on a meridian line in the garden of the abbey of Herkenrode in Hasselt (Flanders in Belgium)

Lambert dials

The Lambert dial is another movable-gnomon sundial.[59] In contrast to the elliptical analemmatic dial, the Lambert dial is circular with evenly spaced hour lines, making it an *equiangular sundial*, similar to the equatorial, spherical, cylindrical and conical dials described above. The gnomon of a Lambert dial is neither vertical nor aligned with the Earth's rotational axis; rather, it is tilted northwards by an angle $\alpha = 45° - (\Phi/2)$, where Φ is the geographical latitude. Thus, a Lambert dial located at latitude 40° would have a gnomon tilted away from vertical by 25° in a northerly direction. To read the correct time, the gnomon must also be moved northwards by a distance

$$Y = R \tan \alpha \tan \delta$$

where *R* is the radius of the Lambert dial and δ again indicates the Sun's declination for that time of year.

Altitude-based sundials

Altitude dials measure the height of the sun in the sky, rather than its rotation about the celestial axis. They are not oriented towards true North, but rather towards the sun and generally held vertically. The sun's elevation is indicated by the position of a nodus, either the shadow-tip of a gnomon, or a spot of light. The time is read from where the nodus falls on a set of hour-curves that vary with the time of year. Since the sun's altitude is the same at times equally spaced about noon (e.g., 9am and 3pm), the user had to know whether it were morning or afternoon. Many of these dials are portable and simple to use, although they are not well-suited for travelers, since their hour-curves are specific for a given latitude.

Human shadows

The length of a human shadow (or of any vertical object) can be used to measure the sun's elevation and, thence, the time.[60] The Venerable Bede gave a table for estimating the time from the length of one's shadow in feet, on the assumption that a monk's height is six times the length of his foot. Such shadow lengths will vary with the geographical latitude and with the time of year. For example, the shadow length at noon is short in summer months, and long in winter months.

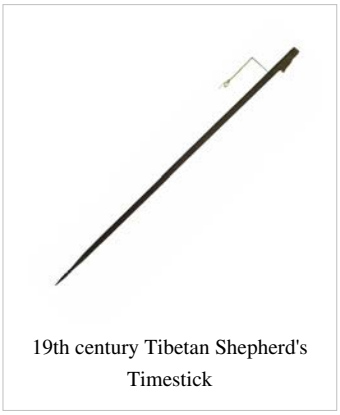
Chaucer evokes this method a few times in his *Canterbury Tales*, as in his *Parson's Tale*

[61]

An equivalent type of sundial using a vertical rod of fixed length is known as a *backstaff dial*.

Shepherd dials –Timesticks

A shepherd's dial — also known as a *shepherds' column dial*,[][] *pillar dial*, *cylinder dial* or *chilindre* — is a portable cylindrical sundial with a knife-like gnomon that juts out perpendicularly.[62] It is normally dangled from a rope or string so the cylinder is vertical. The gnomon can be twisted to be above a month or day indication on the face of the cylinder. This corrects the sundial for the equation of time. The entire sundial is then twisted on its string so that the gnomon aims toward the sun, while the cylinder remains vertical. The tip of the shadow indicates the time on the cylinder. The hour curves inscribed on the cylinder permit one to read the time. Shepherd's dials are sometimes hollow, so that the gnomon can fold within when not in use.



19th century Tibetan Shepherd's Timestick

Shepherd's dials appear in several works of literature. [63]

Similarly, the shepherd's dial is evoked in Shakespeare's *Henry VI, Part 3*, [64]

The cylindrical shepherd's dial can be unrolled into a flat plate. In one simple version,[65] the front and back of the plate each have three columns, corresponding to pairs of months with roughly the same solar declination (June–July, May–August, April–September, March–October, February–November, and January–December). The top of each column has a hole for inserting the shadow-casting gnomon, a peg. Often only two times are marked on the column below, one for noon and the other for mid-morning/mid-afternoon.

Timesticks, *clock spear*,[] or *shepherds' time stick*,[] are based on the same principles as dials.[][] The time stick is carved with eight vertical time scales for a different period of the year, each bearing a time scale calculated according to the relative amount of daylight during the different months of the year. Any reading depends not only on the time of day but also on the latitude and time of year.[] A peg gnomon is inserted at the top in the appropriate hole or face for the season of the year, and turned to the Sun so that the shadow falls directly down the scale. Its end displays the time.[]

Ring dials

In a ring dial (also known as an *Aquitaine* or a *perforated ring dial*), the ring is hung vertically and oriented sideways towards the sun.[66] A beam of light passes through a small hole in the ring and falls on hour-curves that are inscribed on the inside of the ring. To adjust for the equation of time, the hole is usually on a loose ring within the ring so that the hole can be adjusted to reflect the current month.

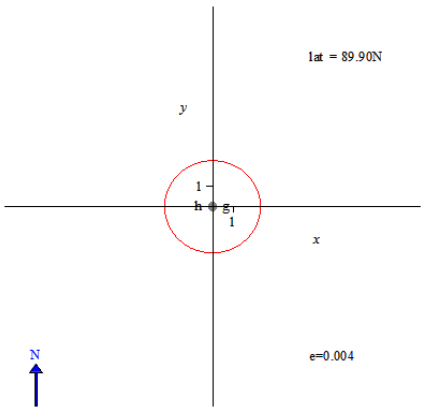
Card dials (Capuchin dials)

Card dials are another form of altitude dial.[67] A card is aligned edge-on with the sun and tilted so that a ray of light passes through an aperture onto a specified spot, thus determining the sun's altitude. A weighted string hangs vertically downwards from a hole in the card, and carries a bead or knot. The position of the bead on the hour-lines of the card gives the time. In more sophisticated versions such as the Capuchin dial, there is only one set of hour-lines, i.e., the hour lines do not vary with the seasons. Instead, the position of the hole from which the weighted string hangs is varied according to the season.

Nodus-based sundials

Another type of sundial follows the motion of a single point of light or shadow, which may be called the *nodus*. For example, the sundial may follow the sharp tip of a gnomon's shadow, e.g., the shadow-tip of a vertical obelisk (e.g., the *Solarium Augusti*) or the tip of the horizontal marker in a shepherd's dial. Alternatively, sunlight may be allowed to pass through a small hole or reflected from a small (e.g., coin-sized) circular mirror, forming a small spot of light whose position may be followed. In such cases, the rays of light trace out a cone over the course of a day; when the rays fall on a surface, the path followed is the intersection of the cone with that surface. Most commonly, the receiving surface is a geometrical plane, so that the path of the shadow-tip or light-spot (called *declination line*) traces out a conic section such as a hyperbola or an ellipse. The collection of hyperbolae was called a *pelekonon* (axe) by the Greeks, because it resembles a double-bladed ax, narrow in the center (near the noonline) and flaring out at the ends (early morning and late evening hours).

Kraków. 50°03′41″N 19°56′24″E [68] The shadow of the cross-shaped nodus moves along a hyperbola which shows the time of the year,indicated here by the zodiac figures. It is 1:50pm on 16 July, 25 days after the summer solstice.



Declination lines at solstices and equinox for sundials, located at different latitudes

There is a simple verification of hyperbolic declination lines on a sundial: the distance from the origin to the equinox line should be equal to harmonic mean of distances from the origin to summer and winter solstice lines.[69]

Nodus-based sundials may use a small hole or mirror to isolate a single ray of light; the former are sometimes called *aperture dials*. The oldest example is perhaps the antiborean sundial (*antiboreum*), a spherical nodus-based sundial that faces true North; a ray of sunlight enters from the South through a small hole located at the sphere's pole and falls on the hour and date lines inscribed within the sphere, which resemble lines of longitude and latitude, respectively, on a globe.[70]

Reflection sundials

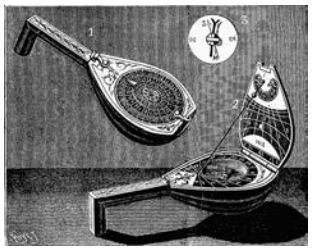
Isaac Newton developed a convenient and inexpensive sundial, in which a small mirror is placed on the sill of a south-facing window.[71] The mirror acts like a nodus, casting a single spot of light on the ceiling. Depending on the geographical latitude and time of year, the light-spot follows a conic section, such as the hyperbolae of the pelikonon. If the mirror is parallel to the Earth's equator, and the ceiling is horizontal, then the resulting angles are those of a conventional horizontal sundial. Using the ceiling as a sundial surface exploits unused space, and the dial may be large enough to be very accurate.

Multiple dials

Sundials are sometimes combined into multiple dials. If two or more dials that operate on different principles — say, such as an analemmatic dial and a horizontal or vertical dial — are combined, the resulting multiple dial becomes self-aligning. In other words, the direction of true North need not be determined; the dials are oriented correctly when they read the same time. This is a significant advantage in portable dials. However, the most common forms combine dials based on the same principle, and thus are not self-aligning.

Diptych (tablet) sundial

The **diptych** consisted of two small flat faces, joined by a hinge.[72] Diptychs usually folded into little flat boxes suitable for a pocket. The gnomon was a string between the two faces. When the string was tight, the two faces formed both a vertical and horizontal sundial. These were made of white ivory, inlaid with black lacquer markings. The gnomons were black braided silk, linen or hemp string. With a knot or bead on the string as a nodus, and the correct markings, a diptych (really any sundial large enough) can keep a calendar well-enough to plant crops. A common error describes the diptych dial as self-aligning. This is not correct for diptych dials consisting of a horizontal and vertical dial using a string gnomon between faces, no matter the orientation of the dial faces. Since the string gnomon is continuous, the shadows must meet at the hinge; hence, *any* orientation of the dial will show the same time on both dials.[73]



Diptych sundial in the form of a lute, c. 1612. The gnomons-style is a string stretched between a horizontal and vertical face. This sundial also has a small nodus (a bead on the string) that tells time on the hyperbolic *pelikinon*, just above the date on the vertical face.

Multiface (facet-headed) dials

A common multiple dial is to place sundials on every face of a Platonic solid, usually a cube.[74] Extremely ornate sundials can be composed in this way, by applying a sundial to every surface of a solid object. In some cases, the sundials are formed as hollows in a solid object, e.g., a cylindrical hollow aligned with the Earth's rotational axis (in which the edges play the role of styles) or a spherical hollow in the ancient tradition of the *hemisphaerium* or the *antiboreum*. (See the History section below.) In some cases, these multiface dials are small enough to sit on a desk, whereas in others, they are large stone monuments.

Such multiface dials have the advantage of receiving light (and, thus, telling time) at every hour of the day. They can also be designed to give the time in different time-zones simultaneously. However, they are generally not self-aligning, since their various dials generally use the same principle to tell time, that of a gnomon-style aligned with the Earth's axis of rotation. Self-aligning dials require that at least two independent principles are used to tell time, e.g., a horizontal dial (in which the style is aligned with the Earth's axis) and an analemmatic dial (in which the style is not). In many cases, the multiface dials are erected never to be moved and, thus, need be aligned only once.

Prismatic dials

Prismatic dials are a special case of polar dials, in which the sharp edges of a prism of a concave polygon serve as the styles and the sides of the prism receive the shadow.[75] Examples include a three-dimensional cross or star of David on gravestones.

Unusual sundials

Benoy dials

The Benoy Dial was invented by Walter Gordon Benoy of Collingham in Nottinghamshire. Light may also be used to replace the shadow-edge of a gnomon. Whereas the style usually casts a sheet of shadow, an equivalent sheet of light can be created by allowing the sun's rays through a thin slit, reflecting them from a long, slim mirror (usually half-cylindrical), or focusing them through a cylindrical lens. For illustration, the Benoy Dial uses a cylindrical lens to create a sheet of light, which falls as a line on the dial surface. Benoy dials can be seen throughout Great Britain, such as[76]

Benoy Sun Clock time shown: 6:00pm - 18.00 hours

- Carnfunnock Country Park Antrim Northern Ireland
- Upton Hall British Horological Institute Newark-on-Trent Nottinghamshire UK
- Within the collections of St Edmundsbury Heritage Service Bury St Edmunds[77] UK
- Longleat Warminster Wiltshire UK
- Jodrell Bank Science Centre and Arboretum
- Birmingham Botanical Gardens Edgbaston UK
- Science Museum UK - (inventory number 1975-318)

Bifilar sundial

Discovered by the German mathematician Hugo Michnik, the bifilar sundial has two non-intersecting threads parallel to the dial. Usually the second thread is orthogonal to the first.[78][79]

The intersection of the two threads' shadows gives the solar time.

Digital sundial

A digital sundial uses light and shadow to 'write' the time in numerals rather than marking time with position. One such design uses two parallel masks to screen sunlight into patterns appropriate for the time of day.

Analog calculating sundial

A horizontal sundial with a face cut on a cardioid keeps clock time, while still resembling a conventional garden sundial. The cardioid shape connects the intersections between the solar-time marks of a conventional sundial, and the equal-angles of a true clock-time face. The place where The shadow crosses the cardioid's edge, and the clock time can be read from the underlying clock-time dial. The sundial is adjusted for daylight saving time by rotating the underlying equal-angle clock-time face. The sun-time face does not move.

Globe dial

The globe dial is a sphere aligned with the Earth's rotational axis, and equipped with a spherical vane.[80] Similar to sundials with a fixed axial style, a globe dial determines the time from the Sun's azimuthal angle in its apparent rotation about the earth. This angle can be determined by rotating the vane to give the smallest shadow.

Noon marks

The simplest sundials do not give the hours, but rather note the exact moment of 12:00 noon. [81] In centuries past, such dials were used to correct mechanical clocks, which were sometimes so inaccurate as to lose or gain significant time in a single day.

In U.S. colonial-era houses, a noon-mark can often be found carved into a floor or windowsill.[82] Such marks indicate local noon, and they provide a simple and accurate time reference for households that do not possess accurate clocks. In modern times, some Asian countries, post offices have set their clocks from a precision noon-mark. These in turn provided the times for the rest of the society. The typical noon-mark sundial was a lens set above an analemmatic plate. The plate has an engraved figure-eight shape., which corresponds to plotting the equation of time (described above) versus the solar declination. When the edge of the sun's image touches the part of the shape for the current month, this indicates that it is 12:00 noon.

Noon-mark from the Greenwich Royal Observatory. The analemma is the narrow figure-8 shape, which plots the equation of time (in degrees, not time, 1°=4minutes) versus the altitude of the sun at noon at the sundial's location. The altitude is measured vertically, the equation of time horizontally.

Noon cannon

A noon cannon, sometimes called a 'meridian cannon', is a specialized sundial that is designed to create an 'audible noonmark', by automatically igniting a quantity of gunpowder at noon. These were novelties rather than precision sundials, sometimes installed in parks in Europe mainly in the late 18th or early 19th century. They typically consist of a horizontal sundial, which has in addition to a gnomon a suitably mounted lens, set up to focus the rays of the sun at exactly noon on the firing pan of a miniature cannon loaded with gunpowder (but no ball). To function properly the position and angle of the lens must be adjusted seasonally.

Meridian lines

A horizontal line aligned on a meridian with a gnomon facing the noon-sun is termed a meridian line and does not indicate the time, but instead the day of the year. Historically they were used to accurately determine the length of the solar year. Examples are the Bianchini meridian line in Santa Maria degli Angeli e dei Martiri in Rome, and the Cassini line in San Petronio Basilica at Bologna.

Sundial mottoes

The association of sundials with time has inspired their designers over the centuries to display mottoes as part of the design. Often these cast the device in the role of *memento mori*, inviting the observer to reflect on the transience of the world and the inevitability of death. "Do not kill time, for it will surely kill thee." Other mottoes are more whimsical: "I count only the sunny hours," and "I am a sundial and I make a botch / of what is done far better by a watch." Collections of sundial mottoes have often been published through the centuries.

Using a sundial as a compass

If a horizontal-plate sundial is portable and is made for the latitude in which it is being used, and if the user has a watch and the necessary information to calculate the local sundial time from its reading, the sundial can be used to find the directions of True North, South, etc. The sundial should be placed on a horizontal surface, and rotated about a vertical axis until it shows the correct time. The gnomon will then be pointing to the North, in the northern hemisphere, or to the South in the southern hemisphere. This method is much more accurate than using the watch as a compass (see watch) and can be used in places where the magnetic declination is large, making a magnetic compass unreliable.

References

Footnotes

[1] Waugh 1973, p. 35.
[2] http://bibref.hebtools.com/?book=%20Isaiah&verse=38:8&src=HE
[3] http://bibref.hebtools.com/?book=II%20Kings&verse=20:9&src=HE
[4] In some technical writing, the word "gnomon" can also mean the perpendicular height of a nodus from the dial plate. The point where the style intersects the dial plate is called the *gnomon root*.
[5] Rohr 1965, pp. 126–129.
[6] Waugh 1973, pp. 124–125.
[8] http://tools.wmflabs.org/geohack/geohack.php?pagename=Sundial&params=39.9157_N_116.3904_E_type:landmark&title=Forbidden+City+equatorial+sundial
[9] Rohr 1965, pp. 46–49.
[10] Mayall & Mayall 1938, pp. 55–56, 96–98, 138–141.
[11] Waugh 1973, pp. 29–34.
[13] Rohr 1965, pp. 49–53.
[14] Mayall & Mayall 1938, pp. 56–99, 101–143, 138–141.
[15] Waugh 1973, pp. 35–51.
[16] Rohr 1965, p. 52.
[17] Waugh 1973, p. 45.
[18] http://tools.wmflabs.org/geohack/geohack.php?pagename=Sundial&params=52.827469_N_0.657616_E_type:landmark&title=Houghton+Hall+vertical+sundials
[19] Mayall & Mayall 1938, pp. 557–58, 102–107, 141–143.
[20] Waugh 1973, pp. 52–99.
[21] Rohr 1965, p. 65.
[22] Waugh 1973, p. 52.
[23] Rohr 1965, pp. 54–55.
[24] Waugh 1973, pp. 52–69.
[25] Waugh 1973, p. 83.
[26] Cite web|Title=Worldwide Sunrise and Sunset map|URL=http://www.sunrisesunsetmap.com/
[27] Rohr 1965, pp. 55–69.
[28] Mayall & Mayall 1938, p. 58.
[29] Waugh 1973, pp. 74–99.
[30] Waugh 1973, p. 55.
[31] Rohr (1965), p. 72; Waugh (1973), pp. 70–73; Mayall and Mayall, pp. 58, 107–112.
[32] Rohr (1965), pp. 55–69; Waugh (1973), pp. 74–99; Mayall and Mayall (1994), pp. 58, 112–117, 145–146.
[33] Rohr (1965), p. 79.

[34] Mayall and Mayall, p. 238.
[35] Rohr (1965), pp. 70–81; Waugh (1973), pp. 100–107; Mayall and Mayall (1994), pp. 59–60, 117–122, 144–145.
[36] Rohr (1965), p. 77; Waugh (1973), pp. 101–103;
[37] Rohr (1965), pp. 76–81; Waugh (1973), pp. 106–107; Mayall and Mayall, 122–125.
[38] Rohr (1965), pp. 77–78.
[39] Rohr (1965), pp. 78–79; Waugh (1973), pp. 106–107; Mayall and Mayall, 59–60.
[40] Rohr (1965), p. 78.
[41] http://tools.wmflabs.org/geohack/geohack.php?pagename=Sundial&params=50_55_47_N_5_20_31_E_type:landmark&title=Hasselt+equatorial+bow+sundial
[42] Rohr 1965, pp. 114, 1214–125.
[43] Mayall & Mayall 1938, pp. 60, 126–129, 151–115.
[44] Waugh 1973, pp. 174–180.
[45] Rohr 1965, p. 17.
[46] Rohr 1965, pp. 118–119.
[47] Mayall & Mayall 1938, pp. 215–216.
[48] http://tools.wmflabs.org/geohack/geohack.php?pagename=Sundial&params=50.4231_N_6.2017_E_type:landmark&title=Belgium
[49] http://toolserver.org/~para/GeoCommons/earth.php?latdegdec=50.4231&londegdec=6.2017&scale=10000&amp&commons=1/
[50] An example of such a half-cylindrical dial may be found at Wellesley College in Massachusetts. name="FOOTNOTEMayallMayall94">Mayall Mayall, p. 94.
[51] Waugh 1973, pp. 48–50.
[54] Waugh (1973), p. 157.
[55] Swanick, Lois Ann. *An Analysis Of Navigational Instruments In The Age Of Exploration: 15th Century To Mid-17th Century*, MA Thesis, Texas A&M University, December 2005
[56] Turner, 1980, p25
[57] May, William Edward, *A History of Marine Navigation*, G. T. Foulis & Co. Ltd., Henley-on-Thames, Oxfordshire, 1973, ISBN 0-85429-143-1
[58] Analemmatic sundials: How to build one and why they work by C.J. Budd and C.J. Sangwin
[59] Mayall and Mayall, pp. 190–192.
[60] Rohr (1965), p. 15; Waugh (1973), pp. 1–3.
[61] Chaucer:as in his *Parson's Tale*. It was four o'clock according to my guess,
Since eleven feet, a little more or less,
my shadow at the time did fall,
Considering that I myself am six feet tall.
[62] Rohr (1965), pp. 109–111; Waugh (1973), pp. 150–154; Mayall and Mayall, pp. 162–166.
[63] For example, in the Chaucer's *Canterbury Tales*, the monk says, "Goth now your wey," quod he, "al stille and softe,
And lat us dyne as sone as that ye may;
for by my chilindre it is pryme of day."
[64] Henry VI, Part 3:O God! methinks it were a happy life
To be no better than a homely swain;
To sit upon a hill, as I do now,
To carve out dials, quaintly, point by point,
Thereby to see the minutes, how they run--
How many makes the hour full complete,
How many hours brings about the day,
How many days will finish up the year,
How many years a mortal man may live.
[65] Waugh (1973), pp. 166–167.
[66] Rohr (1965), p. 111; Waugh (1973), pp. 158–160; Mayall and Mayall (1994), pp. 159–162.
[67] Rohr (1965), p. 110; Waugh (1973), pp. 161–165; Mayall and Mayall (1994), p. 166–185.
[68] http://tools.wmflabs.org/geohack/geohack.php?pagename=Sundial&params=50.0614_N_19.9400_E_type:landmark&title=Krak%C3%B3w+sundial
[70] Rohr (1965), p. 14.
[71] Waugh (1973), pp. 116–121.
[72] Rohr (1965), p. 112; Waugh (1973), pp. 154–155; Mayall and Mayall, pp. 23–24.
[73] Waugh (1973), p. 155.
[74] Rohr (1965),, p. 118; Waugh (1973), pp. 155–156; Mayall and Mayall, p. 59.
[75] Waugh (1973), pp. 181–190.
[76] List correct as of British Sundial Register 2000.
[78] Bifilar sundial (http://www.nonvedolora.it/english/bifilare_en.htm)

[79] Cadran Bifilaire
[80] Rohr (1965), pp. 114–115.
[81] Waugh 1973, pp. 18–28.
[82] Mayall & Mayall 1938, p. 26.

Citations

Bibliography

- Earle AM (1971). *Sundials and Roses of Yesterday*. Rutland, VT: Charles E. Tuttle. ISBN 0-8048-0968-2. LCCN 74142763 (http://lccn.loc.gov/74142763). Reprint of the 1902 book published by Macmillan (New York).
- A.P. Herbert, *Sundials Old and New*, Methuen & Co. Ltd, 1967.
- Mayall, RN; Mayall (1938). *Sundials: Their Construction and Use* (3rd (1994) ed.). Cambridge, MA: Sky Publishing. ISBN 0-933346-71-9.
- Hugo Michnik, *Theorie einer Bifilar-Sonnenuhr*, Astronomishe Nachrichten, 217(5190), p. 81-90, 1923
- Daniel, Christopher St.J.H. (2004). *Sundials*. Shire Album **176** (2nd revised ed.). Shire Publications. ISBN 978-0747805588.
- Rohr, RRJ (1996). *Sundials: History, Theory, and Practice* (translated by G. Godin ed.). New York: Dover. ISBN 0-486-29139-1. Slightly amended reprint of the 1970 translation published by University of Toronto Press (Toronto). The original was published in 1965 under the title *Les Cadrans solaires* by Gauthier-Villars (Montrouge, France).
- Frederick W. Sawyer, *Bifilar gnomonics*, JBAA (Journal of the British Astronomical association), 88(4):334–351, 1978
- Turner, Gerard L'E, *Antique Scientific Instruments*, Blandford Press Ltd. 1980 ISBN 0-7137-1068-3
- J. L. Heilbron, *The sun in the church: cathedrals as solar observatories,* Harvard University Press, 2001 ISBN 978-0-674-00536-5.
- *Make A Sundial*, (The Education Group British Sundial Society) Editors Jane Walker and David Brown, British Sundial Society 1991 ISBN 0-9518404-0
- Waugh, Albert E (1973). *Sundials: Their Theory and Construction*. New York: Dover Publications. ISBN 0-486-22947-5.
- Ralf Kern: Wissenschaftliche Instrumente in ihrer Zeit. Vom 15. – 19. Jahrhundert. Verlag der Buchhandlung Walther König 2010, ISBN 978-3-86560-772-0
- Denis Savoie, *Sundials, Design, Construction, and Use*, Springer, 2009, ISBN 978-0-387-09801-2.

External links

- abrégé de gnomonique (http://www.priceminister.com/s/traité+abrégé+de+gnomonique"Traité), Francis Ziegeltrum, auto-édition, 2010, ISBN 978-2-7466-1913-5
- "Illustrating Shadows", Simon Wheaton-Smith, ISBN 0-9765286-8-1, LCN: 2005900674
  - Also see "Illustrating More Shadows", Simon Wheaton-Smith, both books are over 300 pages long.
- Understanding sundials through map projections (http://wvaughan.org/sundials.html)
- The Ancient Vedic Sun Dial (http://www.vedicastro.com/astronomy5.asp)
- Analemmatic Sundial at Tanglewood (http://gonewengland.about.com/od/massachusettspictures/ss/Tanglewood-Photos_6.htm)
- Asociación Amigos de los Relojes de Sol (http://relojesdesol.info/) (AARS) - Spanish Sundial Society
- British Sundial Society (http://www.sundialsoc.org.uk/)
- Commission des Cadrans Solaires de la Société Astronomique de France (http://www.commission-cadrans-solaires.fr)
- Coordinamento Gnomonico Italiano (http://www.gnomonicaitaliana.it/) (CGI) - Italian Sundial Society

- Derbyshire Sundials (http://www.pandy.me.uk/sundials/) - Sundial Calculators
- North American Sundial Society (http://www.sundials.org/)
- Register of Scottish Sundials (http://www.sundialsofscotland.co.uk/)
- Societat Catalana de Gnomònica (http://www.gnomonica.cat/) - Catalonian Sundial Society
- De Zonnewijzerkring (http://www.de-zonnewijzerkring.nl/eng/) - Dutch Sundial Society (in English)
- Zonnewijzerkring Vlaanderen (http://www.zonnewijzerkringvlaanderen.be/) - Flemish Sundial Society

Historical

- "The Book of Remedies from Deficiencies in Setting Up Marble Sundials" (http://www.wdl.org/en/item/2841) is an Arabic manuscript from 1319 about timekeeping and sundials.
- "Small Treatise on the Calculation of Tables for the Construction of Inclined Sundials" (http://www.wdl.org/en/item/4260) is another Arabic manuscript, from the 16th century, about the mathematical calculations used to create sundials. It was written by Sibt al-Maridini.

Article Sources and Contributors

History of navigation *Source*: http://en.wikipedia.org/w/index.php?oldid=549864940 *Contributors*: Athenean, Bjalmeida, Bmcln1, CaptainHaddock, Casini1, Charles Matthews, Cherubino, Chris the speller, ClovisPt, Colonies Chris, Demeter, DexDor, Dialectric, Durova, Gaius Cornelius, Gun Powder Ma, Haus, Hergilfs, Hmains, JCRB, Jagged 85, Jeancey, Jespinos, Jheald, JonasMeinertz, JustinTime55, LarryJeff, Lotje, Mattg82, McLupy, Michael Daly, Milan Keršláger, Msjerboa, Noodle90, Ohconfucius, OnePt618, Pawyilee, Poetaris, Psychonaut, R'n'B, Ragesoss, Rjwilmsi, SamuelTheGhost, Seanwal111111, Squids and Chips, Tim Zukas, Tom Pippens, Velella, Vgent, WestwoodMatt, Whitehorse1, Woohookitty, XPTO, 44 anonymous edits

Navigation *Source*: http://en.wikipedia.org/w/index.php?oldid=560179892 *Contributors*: (jarbarf), 193.203.83.xxx, 209.239.207.xxx, A-giau, A930913, Aaron Brenneman, Aatomic1, AdamBMorgan, Afalk42, Ahoerstemeier, Ajraddatz, Aladdin Sane, Alansohn, AlexShipping, Allens, Allstarecho, Altenmann, Altermike, Alzarian16, Amaury, Ancheta Wis, Andrejj, Andresruizgonzalez, Angela, Antonio Lopez, Arpingstone, Ashishbhatnagar72, Awien, AxelBoldt, Az1568, B, BD2412, BabyEinstein1, Barticus88, Bazonka, Bearings, Bellhalla, Bidabadi, Big Adamsky, Bigwill0593, Bobblewik, Bobo192, Body1 Inc, Bogey97, Brian0918, Bryan Derksen, Burpen, CJLL Wright, Cacycle, Caltas, CambridgeBayWeather, Captclbecker, Ceyockey, Chetvorno, Chicbicyclist, Chowbok, Chrylis, Cimon Avaro, Ckatz, Click23, Colinpcarr, Colonies Chris, Comancheros, Conversion script, Corn cheese, Costanzo.S, Cottingham, Cxz111, DMacks, DVdm, DabMachine, Dairiki, DanMS, Dancter, Darth Panda, Davandron, DavidLevinson, DePiep, Debresser, Denelson83, Derek Ross, DexDor, Dhollm, Diamond2, Dingar, Discospinster, Doctorhawkes, Download, DragonflySixtyseven, Drift chambers, Dtroupis, E. Fokker, E22weckbacher, Ecook83, Edgar v. Hinüber, Eequor, Egil, Epbr123, EugeneZelenko, Ezhuttukari, Fabartus, Farosdaughter, FastLizard4, Fenyx4, Fheyligh, Fredrik, Frelke, Fuhghettaboutit, Func, GABaker, GCW50, GRAHAMUK, GabrielF, Gaius Cornelius, Gblindmann, Geke, Geoeg, Geof, Giftlite, GoodOlRickyTicky3, GraemeL, Graemesmith, Graymornings, Guoguo12, Haham hanuka, HalfShadow, Haruth, Haus, Head-it-behind, Heron, Hut 8.5, Hydrogen Iodide, I55ere, IW.HG, Icairns, Innv, Ixfd64, J Greb, J.delanoy, JDCMAN, Jaime Saldarriaga, Jannej, Jeremy89442, Jerzy, Joey-das-WBF, Jrvz, Juansempere, Jyril, KAM, Kablammo, Karada, KeithH, Kingfish, KitSolidor, Kkolodziej, KnowledgeOfSelf, Kosebamse, Kslotte, Kuru, Ladego, Lankiveil, Lawrencekhoo, Lenneth, Lightmouse, Linkspamremover, Linmhall, Little Mountain 5, MK8, MadSurgeon, Magister Mathematicae, Mangoe, Mani1, Mark.murphy, Mashni\Q, Maury Markowitz, Mccready, Michael Daly, Michael Devore, Michael Hardy, Mike Dillon, Mk*, Moink, Mr.Z-man, Mugaliens, Mwanner, Nakon, NawlinWiki, Neiljt, Nemkovethetem, NewEnglandYankee, Nick knowles, Nicolae Coman, Niemeyerstein en, Nk, Noz92, Omnipaedista, Pablogrb, Palapala, Paul Koning, Paul Raftery, Pawyilee, PericlesofAthens, Peter Horn, Philbir, Pjoef, Polisher of Cobwebs, Pollinator, Popsracer, Possum, Powerboat-charter, RP459, RaSla, Raven4x4x, Reboot81, ReidarM, Renesis, Res2216firestar, Revipm, Rich Farmbrough, Richardss60, Rjstott, Rjwilmsi, Roesser, Ronz, Racecarr, Rurik the Varangian, Rüdiger Marmulla, SDC, SPKirsch, Sam Hocevar, Schusch, Sergey chepurin, Shantavira, ShelfSkewed, Shipbob, Shoaler, Shraktu, Sicooke, Sionus, Solitude, Strbenjr, Suldren, Tamaratrouts, Taperunner, Tenro1, The Rambling Man, The Thing That Should Not Be, Thingg, ThomasPusch, Thunderboltz, Tide rolls, Tim Zukas, Timtrent, Timwi, Tjhmom, Tomás Fernández Aúz, Ton0401, Toprabhakar, Torkel, Trackinfo, Trevor MacInnis, Tunda emmanuel, Tungsten, Tuos, Tupran, Ultrasonicspeed, Una Smith, Utcursch, Versus22, Vinsci, Vnvnfls, Wandadubbayou, Wavelength, Webwidget, WojPob, Woohookitty, Yintan, Yngvadottir, Zarcadia, Zazou25, ZimZalaBim, Zvn, Zzuuzz, 384 ,הסרפד anonymous edits

Celestial navigation *Source*: http://en.wikipedia.org/w/index.php?oldid=561744345 *Contributors*: A. Balet, Afalk42, Agateller, Allens, Alvesgaspar, Andresruizgonzalez, Arcturus, ArnoldReinhold, Aymankamelwiki, Beland, Bethpage89, BoH, Bongomatic, Cacycle, Cdory28, Celestialmechanic, Chelt, Chris Roy, Chris55, Dashiellx, DerHexer, Derek Ross, Dgroseth, Djdaedalus, Dpm64, Dulciana, Dysepsion, Eequor, Frelke, GCW50, GS3, Gaius Cornelius, Ggreybeard, Gob Lofa, GoingBatty, Gottlob Frege, Haljammy, Haus, Heron, Hkiernan, Hmains, HomerWiki, Honza.havlicek, Ida Shaw, Inane Imp, Indefatigable, Itai, Izno, J-stan, Jaganath, Jamelan, Jim1138, Jinian, John of Reading, Jonkerz, Joris Gillis, Jrvz, Julesd, Jvahey, Kauczuk, KenWalker, Keshiklabs, Ketiltrout, Kosebamse, Kouhoutek, Kubanczyk, Latka, Lightmouse, Macbode, Mark.murphy, Markus Kuhn, Matthewcgirling, Maury Markowitz, Mccready, Metron4, Michael Daly, Michael Hardy, Midgrid, Mmeijeri, Mugaliens, Mwanner, Nigelj, Njaelkies Lea, Novangelis, Oceco, OtterSmith, Paine Ellsworth, Patrick, Paul Koning, Pietrow, Pinethicket, Porpoiseman, Radagast83, Ray Van De Walker, Red Slash, Rich Farmbrough, Rogerzilla, RoySmith, SV Resolution, SamuelTheGhost, Saros136, SaxTeacher, Scriberius, Sexybomber, Shadegan(goru), Sintaku, Siulung808, Sonjaaa, Stwalkerster, Summerdrought, TerpInHotLanta, Testcheck, Thegrtman, Tide rolls, Tim Zukas, Timtwickham, Tpbradbury, Trollderella, Tsgttucker, Turettn, Vegaswikian, Vinsci, Vsmith, Warlord88, Welkinridge, Wer900, Wik, Woodland2004, Woohookitty, Xerxes314, Yestertech, ,אורית ה ,.ماني, 175 anonymous edits

Sextant *Source*: http://en.wikipedia.org/w/index.php?oldid=555609329 *Contributors*: $einte, 1exec1, AAlha, Aarchiba, Acdx, Adashiel, Aiolosply, Alansohn, Alexf, Allamiro, Alvaro, Alvesgaspar, AndrewWTaylor, Aruton, Asclepius, Astrologist, Avoided, AxelBoldt, Bart133, Basawala, Bassbonerocks, Behtis, Benea, Bethling, Bikeable, Blastwizard, Blustar2000, Bozoid, Brandondudecool, Bryan Derksen, Caiyu, Can't sleep, clown will eat me, CarlFeynman, Cdory28, Chick213, Christopher Parham, Cit helper, CommonsDelinker, Conversion script, Corpx, Courcelles, Crohnie, Cus07, Da Joe, David.Monniaux, Dawnseeker2000, Den fjättrade ankan, Denelson83, DerHexer, Doc glasgow, DocWatson42, Dolphin51, Dominictroc, DoubleBlue, Eequor, El C, Entropeter, Erik9, Euchiasmus, Everyking, Excirial, Fltchr, GCW50, Gago Coutinho and Sacadura, Gaius Cornelius, Gblaz, Gene Nygaard, Giftlite, Glenn, Gmaxwell, Gob Lofa, Gogo Dodo, Grimhelm, Hailey C. Shannon, Halda, Haus, Henry W. Schmitt, Heron, Hfink, Hooperbloob, Ian Dunster, Icairns, Instinct, Intery, Isis, J.delanoy, JNW, Jagged 85, Jic, Jim Douglas, Jnordb, JoJan, John 00110, JohnOwens, Juuitchan, Karl-Henner, Karthiknd, KenWalker, Kingpin13, Kjoonlee, Klilidiplomus, Kosebamse, Leonardo212, Lightmouse, Lmzilla, Loganwilliams95, Looxix, Lowe4091, Luccas, Lugia2453, Luna Santin, Lwollert, Magister Mathematicae, Mani1, Martarius, Mdebets, Michael Daly, Michael Zimmermann, Minesweeper.007, Monterey Bay, Msblueras, Mysid, NawlinWiki, Nicboyde, Nigelj, Nivix, Oleg Alexandrov, Omnipotence407, Orangutan, Orwant, Oxymoron83, Paigeluvsphil, Pauli133, Periscopefilm, Peruvianllama, Peter Karlsen, Peter R Hastings, Pharaoh of the Wizards, Philip Trueman, Pigman, Postmortemjapan, Puckly, QuaeriSolet, Quartermaster, Qutezuce, R'n'B, R. fiend, Ralph Sleigh, Rama, Ray Van De Walker, RayKiddy, Restre419, Rgoodermote, Rich Farmbrough, Richardss60, Rivertorch, Rjstott, Rjwilmsi, Rlee0001, Rotkraut, RoyBoy, RoySmith, SV Resolution, Sam Korn, Saros136, Scriberius, Secret Squïrrel, Shadegan(goru), Shlomke, Sionus, Smyth, Snoyes, SorryGuy, Surv1v4l1st, Swatjester, Swimp000, Taliska1, The Obento Musubi, Thingg, ThinkEnemies, Tim Zukas, Timtwickham, Uncle Dick, Uncool User, Vanished user, Vinsci, Welkinridge, WikiMember57, Woohookitty, Wtmitchell, XJaM, Xinit, Yekrats, Zed Orkin, Zscout370, 346 anonymous edits

Octant (instrument) *Source*: http://en.wikipedia.org/w/index.php?oldid=553646051 *Contributors*: Altenmann, Anthony Appleyard, Astrologist, B.d.mills, Brookie, Chris the speller, Chris55, Crout1, Cyfal, Entropeter, Harburg, Hellbus, Hydrargyrum, Indiana State, Jimmy Pitt, Junnoske, M-le-mot-dit, Michael Daly, Ohconfucius, Olve Utne, Pharaoh of the Wizards, Pjbflynn, Rich Farmbrough, Rjwilmsi, RoySmith, Sax Russell, Stahlkocher1, Stanlekub, Tirthajyoti, Triquetra, Victor, WOSlinker, Woohookitty, Yath, 27 anonymous edits

Backstaff *Source*: http://en.wikipedia.org/w/index.php?oldid=542593264 *Contributors*: Adamgawlowski, Altenmann, Brian0918, Brian1979, Cdory28, Charles Matthews, Eastlaw, Eptin, Garamond Lethe, Hooperbloob, Indon, Insanity Incarnate, Joao.pimentel.ferreira, Kbh3rd, Materialscientist, Mcapdevila, Michael Daly, Mild Bill Hiccup, Mondebleu, Mschlindwein, Ohconfucius, P.legrand, Pjbflynn, Porcupine911, Remuel, Tfr000, Theodl, Timrem, Tolly4bolly, Victor Engel, Widr, Wnloler, Woohookitty, X1011, 30 anonymous edits

Mariner's astrolabe *Source*: http://en.wikipedia.org/w/index.php?oldid=561285695 *Contributors*: Alcmaeonid, Androstachys, Craigallan.za, Dmp717200, GoingBatty, Insanity Incarnate, JQF, Jagged 85, Jason210, Joao.pimentel.ferreira, Kace7, MarkMLl, Michael Daly, Nadeem.navidi, Ohconfucius, PGWG, R'n'B, Smyth, Stolsvik, Woohookitty, Zaqarbal, 17 anonymous edits

Astrolabe *Source*: http://en.wikipedia.org/w/index.php?oldid=561338672 *Contributors*: 16@r, 28421u2232nfenfcenc, Abtinb, Accuruss, Ace-Assasin, Aitias, AlainV, Alansohn, Aleator, Alexius08, Allens, Ancheta Wis, Androstachys, Annielogue, Arad, Ariyamehrr, Astrologist, Awwiki, Aymatth2, Aziz1005, Beit Or, Bkell, Blake Burba, Bob Burkhardt, Bob f it, Bob1960evens, Bobo192, Bombarstic, Brainsynth, Bswag99, Byron Vickers, CJLL Wright, Canglesea, Capricorn42, Captainm, Catalographer, Cavatica, Charles Edward, Charlesdrakew, Chrsyl, Chzz, Cormullion, Courcelles, Cuchullain, Cwmhiraeth, DanMS, Danrok, Darth Panda, Darwinek, David.Monniaux, Dawn Bard, Dbachmann, Deanlaw, Deor, Discospinster, Diyar se, Dmp717200, Don4of4, DonSiano, Drumex, Dthomsen8, Dynaflow, ESUH, ESkog, Ed Poor, Edwinstearns, Eequor, Ekarademir, Elassint, Eranb, Excirial, FF2010, Fastfission, Femto, Flykid, Fmreuronat, FocalPoint, Foregone96, Fox Wilson, Frb ds, FreplySpang, Gaius Cornelius, Gattan, Gazpacho, Gerixau, Glacialfox, Glane23, Gonzo fan2007, Graevemoore, GroveGuy, Gurch, Haemo, Harp, Haruth, Hcovitz, Headbomb, Hello71, Heron, Hires an editor, Hmains, Hooperbloob, Hu12, HunterX, IShadowed, IW.HG, Iliada, Isis, J8079s, JFD, JForget, JLaTondre, JLamprey, JYi, JZ230, Jack1956, Jacopo188, Jagged 85, James086, Jbaber, Jic, Joseolgon, Junuxx, Justin benedict, KENROCKZ10, Ka Faraq Gatri, Karl-Henner, Kbh3rd, Khalid Mahmood, Knight1993, Kompere, Krashlandon, Krisyordanov, LOL, Larinma, Lazulilasher, Lboegen, Lboges, Lexicon, Looxix, Lordmaster913, Lugia2453, Maahmaah, Macedonian, Mage, MarkMLl, Matia.gr, Maurog, Menomale, Michael Daly, Michael Hardy, Michaelsanders, Miia, Mjbmr, Mobober, Monty845, Morel, Mukadderat, Mysdaao, NYKevin, Nic bor, Ninly, Novonium, Nsg, Oblivious, Onebravemonkey, Pecher, Per Honor et Gloria, PericlesofAthens, Petri Krohn, Phr, Pimpadaisy1, Prashanthns, Prodego, Pseudothyrum, Pshent, RJHall, Rachack, RadioFan, Ragesoss, Rama, Rayis, Reach Out to the Truth, Reddi, Retodon8, RexNL, Rich Farmbrough, Rick Versteeg, Rjwilmsi, Ron B. Thomson, RossF18, Rursus, Ruud Koot, Ryanmcdaniel, SU Linguist, Sacbob, Salvadorjo, Sam Hocevar, Samuel Grant, SamuelTheGhost, Samuella, Samw, Sarrus, Scjessey, Seanwal111111, Sgcook, Shell Kinney, Shii, Shlomke, Singinglemon, Sj, Skeptic2, Smerdakas, Snowolf, Solipsist, Sonbal Boantjies, Sorchah, Spettro9, Ssorca, Stenning749, SteveMcCluskey, Striver, Syncategoremata, Teh tennisman, Telso, Theodore7, Thingg, Throwawayhack, Thumperward, Tide rolls, Tim1357, Timc, Titoxd, Tnxman307, Tobby72, Topaz, Trevayne08, UncleKensson, UnreferencedVariable, Utziputz, Vgent, Vicki Rosenzweig, Vsmith, WarrenA, Wassermann, Wgzzr, Wic2020, Widr, WikHead, Wikimol, Wikiwhatnot, Willking1979, Woohookitty, Wtshymanski, XJaM, XPTO, Xact, Xashaiar, Zereshk, Zuhairali, ZxxZxxZ, Δ, راند 1991, على ويكى, 420 anonymous edits

Jacob's staff *Source*: http://en.wikipedia.org/w/index.php?oldid=558609415 *Contributors*: Alai, Andkore, AndrewHowse, Arnoutf, AxelBoldt, Cdory28, Cherubino, ChrisCork, DARTH SIDIOUS 2, Dellant, Dominus, Evrik, GeeJo, Gidonb, Gilisa, Gun Powder Ma, Hmains, Ida Shaw, Jagged 85, Jnothman, Joao.pimentel.ferreira, João Miguel Marcelino, Klipdas, Krenakarore, Maestlin, Mcapdevila, Michael Daly, Mimimaka, Oitar, Paul McLaughlin, PericlesofAthens, Piast93, Plucas58, Polylerus, Ragesoss, RandomCritic, Rjwilmsi, Ryanmcdaniel, Spacepotato, Tamorlan, Urgos, Willtron, Woohookitty, Yintan, 46 anonymous edits

Latitude *Source*: http://en.wikipedia.org/w/index.php?oldid=560035950 *Contributors*: 1158pd, Ac44ck, Acroterion, Addshore, AdiJapan, AdrianSavage, Adziura, Afasmit, Alanfeynman, Alansohn, Alphax, Anclation, Andrejj, AndrewWTaylor, AndrewWatt, Animum, Antandrus, Arafel2, Arakunem, Ashishbhatnagar72, AugPi, Avnjay, Avono, Badanedwa, Badly Bradley, Bazonka, Beeblebrox, Ben Ben, Berryz666, Betterusername, Birkett, Bleh999, Blehfu, Bobblewik, Bobo192, Bongwarrior, Bryan Derksen, ButOnMethItIs, Caltas, CambridgeBayWeather, Camilo Sanchez, Camw, Can't sleep, clown will eat me, CanDo, CarpenterA, Cburnett, Cffk, Chaser, Chuckiesdad, Chun-hian, Cimon Avaro, Cirt, Conversion script, Correogsk, Csnewton,

Curps, Cyanrazorcel, D, Dan100, Darth Panda, David Kernow, DavidH, DavidLeighEllis, Davidseed, Dcamp314, Dd2, DeadEyeArrow, DerHexer, Dfrg.msc, Dhruv.mongia, Discospinster, Dlae, Donner60, Doulos Christos, Download, Dragons flight, Dreadstar, Drmies, Drunkenmonkey, Dtwilliamson, Duncharris, Dysepsion, ESkog, Ed g2s, Eeekster, Eequor, Egil, El C, Eleolar, Emezei, Epbr123, Excirial, Eyesnore, Falcon8765, Favonian, Ferhengvan, Fieldday-sunday, FlyingToaster, Fox2k11, Fpoost, Fubfubfub, Futurebird, G.Hagedorn, Gabbi the tabby, Gabiteodoru, Ganesh Paudel, Gene Nygaard, Gerrit, Giftlite, Gilliam, Glenn, Golfandme, Graham87, GregorB, Grim23, Gro-Tsen, Guycalledryan, Gökhan, Haakon K, Henrygb, Histrion, Hut 8.5, Hydrogen Iodide, Icairns, Ilmari Karonen, Indefatigable, Iridescent, Isaac Euler, Isheden, J.delanoy, JH-man, JacobSheehy, Jamo58, Jason Quinn, Jatkins, Jclemens, Jeff G., Jeffz1, Jgrafton, Jim.belk, Jim1138, Jitse Niesen, Joe Kress, Joe2008, Joe3600, John Price, John of Reading, Johndburger, Jojhutton, Jonathan Webley, Jorunn, Julianp, Justlettersandnumbers, Jwolf723, Kaimbridge, Kalamkaar, Kamran the Great, Karol Langner, KasugaHuang, Kbolino, Keilana, Kelly Martin, Ketsuekigata, Kkddkkdd, KnowledgeOfSelf, Kpajko79, Krauss, Kuru, Kylemew, Lacrimosus, Larry Sanger, Larry_Sanger, Latka, Lawrencesm, Leonard G., Lesikar, Light current, Lightmouse, Linkracer, Loadmaster, MBisanz, MKar, Magister Mathematicae, Makeemlighter, Malekhanif, Manfi, Mari0us, Mark.murphy, MarsRover, Martinwilke1980, Mattbash, Mav, Methecooldude, Mets501, Michael Hardy, Microfilm, Mike Dillon, Mmxx, Moe Epsilon, Mongol, MonoAV, Morie.ariel, Mpatel, Mr Winsen1, MrOllie, Mxn, Mygerardromance, Myrtone86, N734LQ, N8chz, NOrbeck, Nascar1996, Natb41, Nathanderthal, NawlinWiki, Ndkartik, NeilN, Neo139, Nestorius, Netnuevo, NewEnglandYankee, Ngopikrishna, Nicolas Perrault III, Nigelj, Niteowlneils, Novickas, Novum, Oekaki, OettingerCroat, Oleg Alexandrov, Onkelschark, Optimist on the run, Orlando F, OwenBlacker, Ozgod, Palapala, Para, Patrick, Paul August, PdDemeter, Penguin, Pepper, Perey, PerryTachett, Peter Mercator, Peter S., Phantomsteve, Phil Boswell, Philip Trueman, Pigsonthewing, Pinethicket, Pinguickman, Pippin254, Pit, Pjrm, Pointergrl, ProfGiles, QuartierLatin1968, R'n'B, R.e.b., RDBury, RJHall, RL0919, Razimantv, Reconsider the static, Richard B, Rjwilmsi, Robert Skyhawk, Romanskolduns, Royboycrashfan, Rracecarr, Rrburke, Rrjanbiah, Rwoolnough, S h i v a (Visnu), SEWilco, SMC, Sacbob, SassyLilNugget, SchfiftyThree, Scooteristi, Scott Burley, Seattlenow, Sephiroth BCR, SetaLyas, Shanel, SharkD, ShelfSkewed, Shereth, Shoefly, Siim, SimonP, Sionus, Sk19842, Skatebiker, Smith609, Snow Blizzard, Solphi, Soyunfurcio, Sparky132, SpawnKillA, Spiffy sperry, Stbalbach, Stephenb, StuRat, Sun Creator, Superbeecat, T-Dog333, TWiStErRob, TakuyaMurata, Tarquin, Tero, The Evil Spartan, The HMB, The wub, TheLedBalloon, TheRanger, Thecpozzoli, Thesevenseas, Tide rolls, Tim Zukas, TimVickers, Tony1, Trigamma, Turian, Ty8inf, Ubergeekguy, Ukexpat, Umapathy, Uncle Milty, Undisclosed14, Utcursch, Vanished user, Versus22, Vina, Violetriga, Vlad2000Plus, Vnmarser, Vsmith, Vssun, Vystrix Nexoth, WAvegetarian, WIKIBoi21, Waltpohl, WatermelonPotion, Waveguy, Wavehunter, Wavelength, Wdanwatts, Wdfarmer, Weetoddid, Widr, WikHead, Wiki alf, Woodstone, Woohookitty, Wumpus3000, WurmWoode, XDnateDX, XJaM, Xgoni, Y2kcrazyjoker4, Yamamoto Ichiro, Yogi de, Zaheen, Zandperl, Zanimum, Zayd1, Zholdas, Zzuuzz, 官翁, 729 anonymous edits

Longitude *Source*: http://en.wikipedia.org/w/index.php?oldid=559316043 *Contributors*: .:Ajvol:., 1158pd, 88crushox242, A2Kafir, A8UDI, Acroterion, AlHalawi, Alanfeynman, Albedo20, Alvesgaspar, Anclation, Andersenman, Andrejj, Andy Dingley, Antandrus, Arthena, Ashishbhatnagar72, Atani, Avihu, Avoided, B jonas, BBird, Badly Bradley, Beland, BenShade, Berryz666, Bhadani, BiT, Big Bird, Binary TSO, BlackShift, Bobo192, Bongwarrior, Boothy443, Brian0918, Burntsauce, Bushdio, CBM, Cabe6403, Cacycle, CambridgeBayWeather, Camipco, Canaima, Canderson7, Cantus, Capricorn42, Captainnomnom22, CaribDigita, CarpenterA, Casmith 789, CharlotteWebb, Chesnok, Christian List, Chun-hian, CielProfond, Cimon Avaro, Cirt, Claude girardin, Closedmouth, Cntras, Coasterlover1994, Conversion script, CosineKitty, Crasshopper, CryptoDerk, Curps, Cuttlefisherman, CyberShadow, Cybercobra, D. Recorder, Daedalus969, DanMS, Dandrake, Dannsuk, Davidawilliams1952, Davidfilmer, Dblanchard, Deagle AP, Deflective, Denelson83, DerHexer, Dhaluza, Dhruv.mongia, Digihoe, Discospinster, Donner60, Doulos Christos, Drmies, Duncharris, Dureo, Edsanville, Edward321, Eequor, Egil, Ekren, Enviroboy, Epbr123, Eskovan, EugeneZelenko, Evaluist, Evertw, FastLizard4, Ferhengvan, Fieldday-sunday, Florian Blaschke, Fredric89, FreplySpang, Frokor, Fubfubfub, Fyrael, Gabbe, Gaelen S., Gaius Cornelius, Ganesh Paudel, Gerrit, Giftlite, Gimboid13, Glenn, Graham87, Gurch, Gyrofrog, Haus, Hbjjfhfkdjhgfdkjhg, Hmains, Hobsonlane, Huttarl, Icairns, Immunize, Instinct, Iridescent, Isaac Euler, Isheden, Isis, It Is Me Here, J-stan, J.delanoy, J36miles, JForget, JJ cool D, Jab843, Jake Nelson, JamesBWatson, January, Jc3s5h, Jclemens, Jeffz1, Jerome Charles Potts, Jerzy, Joe Kress, Joe2008, John of Reading, Jojit fb, Joseph Solis in Australia, Jsawruk, Julianp, Jwolf723, Kaimbridge, Kalamkaar, Karl-Henner, Kazvorpal, Killakopta, Kilmer-san, Kop, Kornfan71, Kpajko79, Krauss, Kubigula, Kwamikagami, LOL, Larry laptop, Latvis, LaurenceV, Lcuff, LeaveSleaves, Leonard G., Les boys, Ligulem, Lillil234, LizardJr8, LlamaDude78, Looxix, Lord of the Pit, LoveActresses, MJCdetroit, MKar, Magister Mathematicae, Manticore, Mapmap, Marek69, Mark Richards, MarsRover, Marshalldunn, Martinwilke1980, Martnym, Mathew5000, Matthead, Mav, Maxumum12, Metmet476, Mia koiszel, Michael Daly, Michael Hardy, Mike Dillon, Mike s, Mineminemine, Moosehadley, MrOllie, Mspraveen, Murtasa, MusicMan4444, Musiphil, Nakon, Naturespace, NawlinWiki, Ng10000, Ngopikrishna, NickelKnowledge, Nigel.gale, Nimmo27, Niteowlneils, Nk, Nothlit, Novangelis, Novum, Oda Mari, OettingerCroat, Oleg Alexandrov, Op. Deo, Orange Suede Sofa, Orlando F, Pablomartinez, PamD, Para, Patrick, Paul August, Paul Koning, Pcb21, Pdn, Peter Horn, Peter Mercator, Pgan002, Pharaoh of the Wizards, Pharos, Pigsonthewing, Piledhigheranddeeper, Pinethicket, Pointergrl, Proofreader77, R'n'B, R.e.b., RR, Racklever, Radon210, Randyorton81, Raven4x4x, RayAYang, RedWolf, Reisio, Renrenren, Res2216firestar, ResearchRave, Revipm, Richard Arthur Norton (1958-), Riley Huntley, Rjstott, RobinClay, Rodasmith, Romanskolduns, Rracecarr, Rrjanbiah, Rror, Russavia, S Hunter Haggard, SEWilco, SGBailey, SV Resolution, Sango123, Saros136, Saturn123456789, Sc147, Sephiroth BCR, Sflanker, Sfoskett, Shanker Pur, SimonP, Sl, Snowolf, Sparky132, Stephanie1953, Stephenb, Stevenj, Strebe, StuRat, Svick, Syrthiss, TWiStErRob, Tabletop, Tarquin, Tenakota123, Terry0051, TheIrishWarden, TheRealJost, TheScurvyEye, Thebestofall007, Thedjatclubrock, Thesevenseas, Thue, Thunderbird2, Tide rolls, Tim Q. Wells, Tim Zukas, Tiptoety, Tobby72, Toddst1, Tolly4bolly, Tom harrison, TomS TDotO, Tommy2010, Tranletuhan, Troymusik, Tuxide, Ukexpat, Urhixidur, UsefulWikipedia, Uxbona, Velella, Versus22, VictorAnyakin, Violetriga, Vsmith, Vssun, Wavelength, Whohe!, Wikitza, William Avery, Wizzy, Woodstone, X201, XJaM, Xiaphias, Yamamoto Ichiro, Youssefsan, Zaheen, Zbayz, Zirland, Zzuuzz, 官翁, 622 anonymous edits

History of longitude *Source*: http://en.wikipedia.org/w/index.php?oldid=561866953 *Contributors*: Benea, Cahill1, Cjmclark, Corruptcopper, Cyan22, Delirium, DexDor, DisplayGeek, DiverDave, Elipongo, Fconaway, Fryed-peach, Fæ, Gottlob Frege, HLHJ, HWSager, Hmains, Joe Kress, Jshafer369, LindsayH, Manoguru, Marek69, Mcapdevila, Meniou, Michael Daly, Michael Hardy, Mountain, Per Honor et Gloria, RHaworth, SchreiberBike, Tdp1001, Woohookitty, 107 anonymous edits

Reflecting instrument *Source*: http://en.wikipedia.org/w/index.php?oldid=502543176 *Contributors*: Chris the speller, Fratrep, Jagged 85, Jimmy Pitt, John of Reading, M-le-mot-dit, Mcapdevila, Michael Daly, Michael Hardy, Rama, Rjwilmsi, Rodhullandemu, Waldir, Woohookitty, Wtshymanski, 18 anonymous edits

Iceland spar *Source*: http://en.wikipedia.org/w/index.php?oldid=561514231 *Contributors*: Alan Liefting, ArniEin, Bearpaw1099, Brian0918, ChrisGualtieri, Chunhuahu, Cuchullain, Darrell Greenwood, Deanlaw, Dominus, Gnarristi, Groyolo, Grrrrrreg, Headbomb, IceKarma, Janfri, JoeSperrazza, Johannessen, JoniFili, Magioladitis, Myasuda, Nishchintsatam, Norrk, Peterlewis, Potatoswatter, Softy, Srleffler, Stevan White, TheLateDentarthurdent, Valfontis, Violetcries, Vsmith, Wetman, WikHead, YUL89YYZ, YakbutterT, 17 anonymous edits

Sunstone (medieval) *Source*: http://en.wikipedia.org/w/index.php?oldid=555088181 *Contributors*: Alan1000, ArniEin, CMG, DexDor, Dustynyfeathers, Hhhippo, Jhendin, JoeSperrazza, Khazar2, Ktr101, Macumba, Michael Snow, Quota, Srleffler, Sun Creator, Tizeff, Vsmith, Whitehorse1, Winterst, Wuhwuzdat, YakbutterT, Yngvadottir, 14 anonymous edits

Sunstone *Source*: http://en.wikipedia.org/w/index.php?oldid=547978709 *Contributors*: A. Parrot, Aboutmovies, Acalamari, Ahoerstemeier, Aitias, Armistej, ArticCynda, Ashley Y, Avneshsh429, Brockert, Bryancpark, C.Fred, Chris.urs-o, Cremepuff222, Dodiad, Donlsimpson, Donsimpson, Drmies, Dustynyfeathers, EoGuy, Eric567, Esprqii, Fda247, Gem-fanat, Gemadventure, Hyperdeath, IronGargoyle, Jantangring, Johantheghost, John R G, Kjkolb, Kyoko, Lookinhere, Melesse, Mikevill1, NewEnglandYankee, Omegatron, Philkon, Pne, Quota, Rvannatta, SDC, Squids and Chips, Srleffler, Svick, Tangledweb555, The PIPE, Valfontis, Vsmith, Whitehorse1, ZachJBeavers, مانی, 52 anonymous edits

Solar compass *Source*: http://en.wikipedia.org/w/index.php?oldid=561699471 *Contributors*: Albemarle, ArniEin, BillHart93, Casablanca2000in, Dismas, Doug Coldwell, FF2010, GSmith1876, Hooperbloob, JDspeeder1, Less Than Free, LilHelpa, Mcapdevila, Misibacsi, Optimist on the run, RP459, SDC, Taciturnn, Tobeprecise, Wodawik, 16 anonymous edits

Astrocompass *Source*: http://en.wikipedia.org/w/index.php?oldid=542548789 *Contributors*: Aaron D. Ball, Closedmouth, Cyfal, Hetar, Infobacker, KharBevNor, Klimot, LilHelpa, Lotje, Magioladitis, Mcapdevila, Neilc, Paul Koning, Pilapila, Scott Sanchez, ShelfSkewed, SimonP, Thumperward, Trjumpet, 4 anonymous edits

Compass *Source*: http://en.wikipedia.org/w/index.php?oldid=561599978 *Contributors*: (jarbarf), ***Ria777, .:Ajvol:., 16@r, 2C0F:FFD8:1A:1B0C:3C50:62BF:28C3:789C, 49oxen, 4twenty42o, A3RO, A930913, ABF, AGK, AHMartin, Aaron McDaid, Acroterion, Addshore, AdjustShift, Adrian.benko, Aesopos, Afluent Rider, Agamemnus, Ahoerstemeier, Ahunt, Aitias, Ajraddatz, Alansohn, Alexf, Alfio, Allstarecho, Altenmann, Altes2009, Amplitude101, AnakngAraw, Anarchyboy, Anbu121, Ancheta Wis, Anclation, Andrew2536, Anpersonalaccount, Antandrus, Anthony Appleyard, Anthony Nolan O'Nymous, ArielGold, Armando, Arpingstone, Arsonal, Artobest, Aruton, Arx Fortis, Aspenocean, AssegaiAli, Audriusa, Avenged Eightfold, BRPXQZME, Backslash Forwardslash, Badamsambu, Badly Bradley, Balthazarduju, Bauple58, Beach drifter, BenWilliamson, Benjwong, BernardZ, Betacommand, Bfigura's puppy, Big Brother 1984, Bigdottawa, Billlion, Blaxthos, BlueDevil, BobKawanaka, Bobblewik, Bobo192, Bongwarrior, Boris Barowski, Brandon, Brekdanser, Brian0918, Brockert, Bryan Derksen, Bsadowski1, Bucketsofg, Burwellian, Byron Vickers, CTF83!, CWii, Cacophony, Caiqian, Caltas, Calvin Lourdes He, CambridgeBayWeather, CanOfWorms, CanadianLinuxUser, Canderson7, Canyouhearmenow, Cbramble, Cesiumfrog, Cfailde, CharlieEchoTango, Chetvorno, Chmod007, Chris 73, Chris55, ChrisGualtieri, Chrishmt0423, Chrislk02, Ciaccona, ClamDip, Clayhalliwell, Clear range, Cmh, Cold Season, Cometstyles, Comte0, Cool Blue, Coolpatj, Corpx, Courcelles, Cruise Callen, CyberDragon777, Cyfal, D.D.Jacko, DARTH SIDIOUS 2, DGG, DJBullfish, DMacks, DOwenWilliams, DVD R W, Damicatz, Dancter, DanielDeibler, Dante Alighieri, Davewild, David Powers, Dawn Bard, Dbam, Dcljr, Dellant, Denelson83, DerHexer, Derek geary, Devanampriya, Dewritech, Diannaa, Dirrahman, Discospinster, DisillusionedBitterAndKnackered, Dmeranda, Doctordestiny, Dolphin51, Don4of4, Doolotbek e, Dpwkbw, Drf5n, Drunkenmonkey, Dusk shadow187, Dv82matt, E Wing, EJF, ESkog, Eaglecap Backpack, EdC, Edgar181, Edison, Eequor, Efrainvasquez5th, ElinorD, Enderpearl, Enviroboy, Epbr123, Erik Neves, Error -128, Est.r, Ethulin, EugeneZelenko, Eurosong, Everyking, Eyesnore, Fabartus, Farosdaughter, FelisLeo, Fetchcomms, Fieldday-sunday, Flewis, Fluffernutter, FocalPoint, FrankFlanagan, Freeksquad, Full Shunyata, Fæ, Gaff, Gail, Galorr, Gareth Griffith-Jones, GhostPirate, Giftlite, Ginsengbomb, GipeDZ, Gisling, Gj7, Glane23, Glass Sword, Glenn, Gogo Dodo, GoingBatty, Gothicartech, Grahamperrin, Grimey109, Gun Powder Ma, Gurch, Gwernol, Gwinva, Hadal, Haiduc, Hairy Dude, HamburgerRadio, Hammer1980, Hanchi, Harburg, Harry Bull, Hashim321, Hayabusa future, Hdrhedt, Heqs, Heracles31, Heron, Hgrobe, HiLo48, Hilittledork, Hmrox, Hogyn Lleol, Hookey-rox, Hooperbloob, Horselover Frost, Hottentot, Husond, Hydrargyrum, IRelayer, Icairns, Imjustmatthew, Indy muaddib, Inisheer, Insanity Incarnate, Intranetusa, IntroNats101, Inwind, Iridescent, Irishguy, IronGargoyle, Itai, J.delanoy, J8079s, JForget, Jacobharrisonrichter, Jagged 85, James Lum K.H., JamesR, Jameslwoodward, Jaypee1, JaypeeUS, Jcpenny115632, Jeff G., Jeff3000, Jeltz, Jiddisch, Jim.henderson, Jim1138, Jinian, Jiy, Jlittlenz, JoJaysius, Joconnor, Joel7687, John, John Andersson (WMSE), John Cline, John K, John of Reading, JohnOwens, Johnh123, JohnnyJohnny, Jojhutton, Jorgenev, Jose77, Jrvz, Jsmn4vu, Julesomega, Juliancolton, Jusdafax, K Eliza Coyne, KAM, KGasso, Kamal Chid, Kamek98, Kanags, Katalaveno, Katimawan2005, Katpatuka, Kaykaykaykay, Keahapana, Keilana, Keycard, KharBevNor, Khazar2, Kingpin13, Kingturtle, Kitkater, Kjl123, Klimot, Knurdtech, Knutux, Koavf, Kobalt64, Krish94, Kslotte, Kubigula, Kuru, Kwiki, LOTRrules, La goutte de pluie,

Lawrencekhoo, Lazulilasher, Leanwitit, LeaveSleaves, LedgendGamer, Lexi Marie, Lightmouse, LilHelpa, LinDrug, Ling.Nut, Linkspamremover, LjL, Local hero, Logan, Lord Pistachio, LordHarris, Loren Rosen, LtPowers, Lugia2453, Luk, Luna Santin, Madden88, Maddie!, Madman2001, Magi42, Maijinsan, Malinaccier, Man vyi, Mani1, Marek69, Mark.murphy, Marquez, Martinlc, Master of the Oríchalcos, Materialscientist, Max Naylor, Maxamegalon2000, Mboverload, Mburgard, McSly, Mekong mainstream, Merlion444, Mesconsing, Meters, Methcub, Mgzs180, Mhockey, Michael Daly, Michael Hardy, Mikerom12, Mikhail Ryazanov, Mild Bill Hiccup, Milnews.ca, Mini-Geek, Ministevieg, Mirwin, Mjs1991, Mjsabby, Mjsteiner, Mlessard, Mlybanon, Mmonne, MoRsE, Modulatum, Monkey Bounce, Morgis, Mr. President of the u.s.a., Mspraveen, Mumia-w-18, MusikAnimal, Musiphil, Mwanner, Mygerardromance, N5iln, NHRHS2010, Naddy, Natalie Erin, Natobxl, NawlinWiki, Ne0pets22, NellieBly, NerdyScienceDude, NewEnglandYankee, Neyagawa, Nfe, Nigelj, Nikai, Nk, Nn123645, No Guru, Nommonomanac, NoodleWhacks, Noommos, Nsaa, Nyenyec, O Graeme Burns, Oaktree b, Oceanh, Ohconfucius, Ojigiri, Omg all the good usernames are taken, Onco p53, Oo7565, Orfen, OverlordQ, Oxonhutch, Oxymoron83, Oybubblejohn, PGWG, PMLawrence, Pablomartinez, PaterMcFly, Paul Koning, Paul Mackay, Pax:Vobiscum, Pepper, PericlesofAthens, Petehawk, Peter Ellis, Peter M. Brown, Phanton, Pheifdog, Phgao, Philip Trueman, PhnomPencil, Physis, Piano non troppo, Piepot9, PierreAbbat, PigFlu Oink, Pinethicket, Pit, Polarscribe, Polylerus, Pomona17, Populus, Prodego, ProhibitOnions, Psinu, Python eggs, Qfl247, Quepasahombre, Quinsareth, Qxz, R3venans, RainbowOfLight, Rama, Raryel, RaseaC, Ravedave, Raven in Orbit, Raymondwinn, Reaper Eternal, Reddi, Reinoutr, RevolverOcelotX, RexNL, Rich Farmbrough, Ringomassa, Rjwilmsi, Rkov, Rlhatton, Rob cowie, RockMagnetist, Rogper, Rossami, Rrburke, Rurik the Varangian, Rushbugled13, Ryanmanley, Rygel, SJP, SajmonDK, Salsa Shark, Salvio giuliano, Santryl, Satellizer, Scientific29, Scriberius, Seaphoto, Seb az86556, Secretlondon, Sgt. R.K. Blue, Shannon.cobian, Shantavira, Shavindu Piyadasa, Shkarter1985, Shreevatsa, Siberex, Sietse Snel, SilkTork, Simetrical, Simon12, Simondrake, Sivullinen, Skizzik, Slashme, Slow Riot, Smalljim, Smelialichu, Snow Blizzard, Snowolfd4, SoHome, Someguy1221, SoniaZ, Sonjaaa, SpK, Spellmaster, Spiko-carpediem, Spoonlegs, Springnuts, SpuriousQ, Srushe, Ssilvers, Stabilo boss, Stalefries, Stbalbach, Stephenb, Steven Zhang, Suffusion of Yellow, Sun Creator, Sureiyah1, Suruena, Sus scrofa, Svm2, Swimtrunkcity, Symane, Syncategoremata, THEN WHO WAS PHONE?, Tetraedycal, The Cunctator, The Flying Spaghetti Monster, The Thing That Should Not Be, The undertow, TheLeopard, TheOtherJesse, Thelettuceman, Thewho98, Thingg, Thrixx, Thumperward, Tide rolls, Tim1357, Tobias Bergemann, Tom Pippens, Tom harrison, Tombomp, Tommy2010, Topory, Tpb1093, TransUtopian, Trausten2, Treisijs, Trevor MacInnis, Trjumpet, Trusilver, Tubbs334, Typhoonchaser, Tyranny Sue, Tznkai, UTSRelativity, Udiehte7482, Uditshankar, Ugen64, Uncle Dick, Underorbit, VASANTH S.N., Valfontis, Vanished user aoiowaiuyr894isdik43, Vanished user ikijeirw34iuaeolaseriffic, Vary, Velella, Versus22, Vgy7ujm, Wavelength, Wdfarmer, Webclient101, Wetman, WikHead, WikiLaurent, Will O'Neil, William Avery, Williamlear, Wknight94, WongFeiHung, Woohookitty, WookieInHeat, Yamummasnotbad, Yekrats, Ynhockey, Zereshk, Zidonuke, Zirguezi, Zloyvolsheb, Zmusicman99, Zntrip, Zootsuits, Zro, Zsinj, Zundark, Zzuuzz, Île flottante, 1481 anonymous edits

Sundial *Source*: http://en.wikipedia.org/w/index.php?oldid=561070686 *Contributors*: 2001:7C0:E701:4C34:E433:7CB3:18DE:371B, 84user, 90 Auto, AMK1211, AManWithNoPlan, AcidHelmNun, Aesopos, Ahoerstemeier, Ajh16, Alan Liefting, Alansohn, Alberto Orlandini, Alfranco584, Alton.arts, Alucard (Dr.), Amcbride, Ancheta Wis, Andre Engels, Andrevruas, Archeofoto, Arthena, Asenine, Ashley Y, Ashmedai, Athanasius1, Audriusa, Authalic, Auximines, BRUTE, Bartomeutorres, Beaumont, Beetstra, Belg4mit, Bender235, Bentogoa, Bkell, Bluelion, Blurpeace, Bongwarrior, Braincricket, Brian0918, BrianGV, Bryan Derksen, CLW, CRGreathouse, Calair, CampTenDMS, Can't sleep, clown will eat me, CanOfWorms, CardinalDan, CarolGray, Catsmeat, Cbear225, Celsius1414, Ceoil, Charles Matthews, Chepry, Chris Roy, ChrisGualtieri, ChrisHamburg, Chzz, CielProfond, ClemRutter, Closedmouth, Cmapm, Colfer2, CommonsDelinker, Compay, Complex (de), Courcelles, Csab, Cst17, Cwisehart, D6, DAJF, DOwenWilliams, Darkrokker224, Darwinek, David Fuchs, David R. Ingham, DavidCary, DavidJ710, DavidStern, Dbell5, Delta Tango, Denisarona, Dennis cowan, DerHexer, Dhelor, Dnjansen, Donarreiskoffer, Doug Coldwell, Douglas Hunt, DraxusD, Dreadstar, Dringend, EMU CPA, ERcheck, Ebacci EN, Ebear422, Edal, Edgar181, Edmund Patrick, Eemilyl, Elipro, Emeraldcityserendipity, Enkyklios, Estevoaei, Eubulides, Exor674, Eyesnore, Ezra Wax, Falcon8765, Fanx, Fbv65edel, Ferkel, Ferritecore, Fleck1337, FrancesLey, Freedomtalks, Froid, Fæ, Gamewizard71, Gazimoff, Giftlite, Gilliam, Gimboid13, Ginosal, Ginsengbomb, Granite07, Greudin, GrindtXX, Haemo, Hayabusa future, Henrik, Hgrobe, Hmains, Hookerman, Horology, Howie Green, Hu12, ISasha, IVAN3MAN, Iamlatin, Icarus3, IceDragon64, Ida Shaw, Igoldste, Imc, Indon, Iridia, Irishguy, JQF, JaGa, Jacklee, Jagged 85, JamesAM, Jbergquist, Jc3s5h, Jheald, Jmh649, JoeSmack, Johann Jaritz, John, Johnmahorney, Joopercoopers, Jorunn, Jusdafax, Kaal, Karelj, Karlwk, Karthi4india, Kateshortforbob, Kbrose, Keenan Pepper, Kevin Saff, Kingpin13, Kintetsubuffalo, Kowloonese, Kpjas, Kuak, Kungfuadam, L Kensington, LennartBolks, Leonard G., Leontios, Lightmouse, LilHelpa, Lionsden99, Lir, Lismoreboy, Little Mountain 5, Lkesteloot, Look2See1, Loren.wilton, Luckyherb, Lucylogan, Lumos3, M-le-mot-dit, MER-C, Madeleine Price Ball, Magister Mathematicae, Mani1, Margaret Ferguson Burns, Mark Nez, Mark.murphy, Markeilz, Martim33, Master Jay, Mathew5000, Mcewan, Mdann52, Meganliebnitzxxx, Melsaran, Mgiganteus1, Michael Daly, Michael Devore, Michelet, Mikehelms, Mintrick, Mintylula, Mocoroh, Modeha, Momirt, Mount Flatten, Mr.Z-man, Msablic, Mystykmyk, Nabokov, Naddy, Nafsadh, NatureA16, Nburden, NeilN, Newsaholic, Nolanus, Noorse, Nrbelex, Octahedron80, Op. Deo, Oxymoron83, PAR, Paigemorrison, Pais, Papy77, Para, Patrick-br, Pbroks13, Pc0158, Pecalux, Pekaje, Per Honor et Gloria, PeterRet, Pharaoh of the Wizards, Philip Trueman, Piers, Pinethicket, Polishname, Polylerus, PrestonH, Psychonaut, Pumpu, Pustelnik, Qxz, R'n'B, RG2, RJFJR, RPellessier, RaCha'ar, Rajeshodayanchal, Rama, Raven in Orbit, Ray Van De Walker, Rayray175, Reisio, Retro00064, Rich Farmbrough, Rick Sidwell, Rjhanji, Rjwilmsi, RodC, Ron E, Ronhjones, Ronstew, Rorybowman, Rosser1954, Rrburke, Rugbyhelp, SEWilco, ST47, SamuelTheGhost, SarahStierch, Schwilgue, Scott14, Seduisant, Seraphimblade, Shorelander, Sibian, SimonP, Singinglemon, Some jerk on the Internet, Sonjaaa, Sonneninfo, SpK, Spike Wilbury, Sputnikcccp, Srtxg, Stelmarta, Steven Zhang, Stevensrmiller, Strike Eagle, SunDoggie, SvNH, Sverdrup, Switchercat, Symane, Syncategoremata, THEN WHO WAS PHONE?, TWCarlson, Tagishsimon, Tahmasp, TastyPoutine, Tawker, Tcncv, Tfr000, The Evil IP address, The Thing That Should Not Be, Tide rolls, TonyTheTiger, TransUtopian, Trusilver, Tsujigiri, Ttbya, Tyger27, UberMan5000, Unixplumber, Uusitunnus, Vala M, Van helsing, Vapetino, Vary, Vazgen4, Victor falk, Victuallers, Wasell, West.andrew.g, Whaiapu, Wiggles98, Wiki alf, Wikimol, Wikipelli, Willking1979, WillowW, Willy Leenders, Wilson44691, Wsiegmund, Wtmitchell, XJaM, Xbows, Xenmorpha, Yahia.barie, Yamara, Youssefa, Yuzisee, 720 ,מרוֹל רפאים anonymous edits

Image Sources, Licenses and Contributors

File:World Map 1689.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:World_Map_1689.JPG *License*: Public Domain *Contributors*: en:Gerard van Schagen

Image:NAMA Machine d'Anticythère 1.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:NAMA_Machine_d'Anticythère_1.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: DrJunge, Editor at Large, G.dallorto, German, Herbythyme, Lead holder, Marsyas, 8 anonymous edits

File:Astrolabe-Persian-18C.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolabe-Persian-18C.jpg *License*: Creative Commons Attribution-Share Alike 2.0 Generic *Contributors*: Andrew Dunn

File:Silfurberg.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Silfurberg.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: ArniEin

File:FraMauroDetailedMapInverted.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:FraMauroDetailedMapInverted.jpg *License*: Public Domain *Contributors*: Warburg, Wikiborg, World Imaging, 2 anonymous edits

File:Jacobsstaf.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Jacobsstaf.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Original uploader was Serassot at nl.wikipedia

File:Licht der Zeevaert, Frontispiz.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Licht_der_Zeevaert,_Frontispiz.jpg *License*: Public Domain *Contributors*: Cherubino, Mayer Bruno

File:America noviter delineata.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:America_noviter_delineata.jpg *License*: Public Domain *Contributors*: Jodocus Hondius (1563-1612)

File:Halley compass variations 1702.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Halley_compass_variations_1702.jpg *License*: Public Domain *Contributors*: Edmond Halley

File:Ocean currents 1943 (borderless)3.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Ocean_currents_1943_(borderless)3.png *License*: Public Domain *Contributors*: US army

File:Table of Geography and Hydrography, Cyclopaedia, Volume 1.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Table_of_Geography_and_Hydrography,_Cyclopaedia,_Volume_1.jpg *License*: Public Domain *Contributors*: Brian0918, LaosLos, RedWolf

File:World map longlat.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:World_map_longlat.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Thesevenseas (talk)

Image:World map with equator.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:World_map_with_equator.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Thesevenseas (talk)

File:Cruising sailor navigating.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Cruising_sailor_navigating.jpg *License*: Public Domain *Contributors*: KTo288, KenWalker, Logograph

File:SplitPointLighthouse.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:SplitPointLighthouse.jpg *License*: Public Domain *Contributors*: Original uploader was Danjamz at en.wikipedia

File:Moon-Mdf-2005.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Moon-Mdf-2005.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: ComputerHotline, Lotse, Mdf, WikedKentaur, 2 anonymous edits

File:Decca Navigator Mk 12.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Decca_Navigator_Mk_12.jpg *License*: GNU Free Documentation License *Contributors*: Captain Crunch, Stahlkocher, Tiesse, 1 anonymous edits

File:Radar screen.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Radar_screen.JPG *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Clipper, PeterWD, Pierre cb, Tony Wills, 2 anonymous edits

File:GPS Satellite NASA art-iif.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:GPS_Satellite_NASA_art-iif.jpg *License*: Public Domain *Contributors*: Bricktop, Bryan Derksen, Common Good, Edward, GDK, Jafeluv, Michaelfavor, Savh, Túrelio, 14 anonymous edits

File:Sun-Moon path.PNG *Source*: http://en.wikipedia.org/w/index.php?title=File:Sun-Moon_path.PNG *License*: Public Domain *Contributors*: Rogilbert

File:Marine sextant.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Marine_sextant.svg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Joaquim Alves Gaspar

File:Accuracy of Navigation Systems.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Accuracy_of_Navigation_Systems.svg *License*: Creative Commons Attribution 3.0 *Contributors*: derivative work: Johannes Rössel (talk) Accuracy.png: Unomano

File:Exval.jpeg *Source*: http://en.wikipedia.org/w/index.php?title=File:Exval.jpeg *License*: Public Domain *Contributors*: Andre Engels, Docu, Korrigan, Thuresson, 1 anonymous edits

Image:Marine sextant.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Marine_sextant.svg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Joaquim Alves Gaspar

Image:Sun Moon (annotated).gif *Source*: http://en.wikipedia.org/w/index.php?title=File:Sun_Moon_(annotated).gif *License*: Public Domain *Contributors*: Korrigan, Maksim

Image:Using sextant swing.gif *Source*: http://en.wikipedia.org/w/index.php?title=File:Using_sextant_swing.gif *License*: Creative Commons Attribution-Sharealike 2.5 *Contributors*: Joaquim Alves Gaspar

Image:Sextant.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sextant.jpg *License*: Public Domain *Contributors*: Denniss, Dodo, Ranveig

File:Sekstant.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sekstant.jpg *License*: Public Domain *Contributors*: TOR

File:U.S. Navy officer using a sextant.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:U.S._Navy_officer_using_a_sextant.jpg *License*: Public Domain *Contributors*: Periscopefilm, Taketa

File:Oktant.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Oktant.jpg *License*: GNU Free Documentation License *Contributors*: Oneblackline, Stahlkocher

File:Newton's reflecting quadrant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Newton's_reflecting_quadrant.png *License*: Public Domain *Contributors*: David Brewster

File:Newton quadrant detail.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Newton_quadrant_detail.png *License*: Public Domain *Contributors*: Michael Daly, Pieter Kuiper

File:Hadley's reflecting quadrant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Hadley's_reflecting_quadrant.png *License*: Public Domain *Contributors*: John Hadley

File:Hadley's octant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Hadley's_octant.png *License*: Public Domain *Contributors*: John Hadley

File:Astroscope (instrument).png *Source*: http://en.wikipedia.org/w/index.php?title=File:Astroscope_(instrument).png *License*: GNU Free Documentation License *Contributors*: Michael Daly

File:Octant-notepad.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Octant-notepad.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

File:Octant-scale-and-index.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Octant-scale-and-index.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

File:Octant pinnula and horizon mirror.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Octant_pinnula_and_horizon_mirror.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

File:Davis_quadrant_4.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Davis_quadrant_4.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Mcapdevila

Image:Davis-precursor.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Davis-precursor.png *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

Image:Davis-precursor-2.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Davis-precursor-2.png *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

Image:Davis-quadrant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Davis-quadrant.png *License*: Creative Commons Attribution 3.0 *Contributors*: Michael Daly

Image:Demi-cross.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Demi-cross.png *License*: Creative Commons Attribution-Share Alike *Contributors*: Michael Daly

Image:The-plough-(instrument).png *Source*: http://en.wikipedia.org/w/index.php?title=File:The-plough-(instrument).png *License*: GNU Free Documentation License *Contributors*: Michael Daly

Image:Hood-cross staff.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Hood-cross_staff.png *License*: Public Domain *Contributors*: Thomas Blundeville

Image:Cole-quadrant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Cole-quadrant.png *License*: Creative Commons Attribution-Share Alike *Contributors*: Michael Daly

Image:Cross-bow-quadrant.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Cross-bow-quadrant.png *License*: GNU Free Documentation License *Contributors*: Michael Daly

File:PD-icon.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:PD-icon.svg *License*: Public Domain *Contributors*: Alex.muller, Anomie, Anonymous Dissident, CBM, MBisanz, PBS, Quadell, Rocket000, Strangerer, Timotheus Canens, 1 anonymous edits

File:Lagos44.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Lagos44.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Georges Jansoone

File:Mariner's astrolabe.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Mariner's_astrolabe.jpg *License*: Public Domain *Contributors*: Joao.pimentel.ferreira, Joseolgon

File:Astrolábio Náutico - Aveiro.gif *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolábio_Náutico_-_Aveiro.gif *License*: Public Domain *Contributors*: Joao.pimentel.ferreira, Joseolgon

File:Astrolabe (PSF).png *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolabe_(PSF).png *License*: unknown *Contributors*: Bastique, Igno2, Jak, Karel K., PatríciaR

File:Astrolabe quadrant England 1388.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolabe_quadrant_England_1388.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: PHGCOM

File:astrolab.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolab.JPG *License*: Public Domain *Contributors*: FoeNyx, Maksim, Roomba, W!B:, Wst

File:Tusi manus.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Tusi_manus.jpg *License*: GNU Free Documentation License *Contributors*: Baroc, MGA73, Magog the Ogre, Themightyquill, ZxxZxxZ

File:Jean Fusoris planispheric astrolabe in Putnam Gallery, 2009-11-24.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Jean_Fusoris_planispheric_astrolabe_in_Putnam_Gallery,_2009-11-24.jpg *License*: GNU Free Documentation License *Contributors*: Sage Ross

File:Astrolabe, 18th century, disassembled.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolabe,_18th_century,_disassembled.jpg *License*: Creative Commons Attribution 2.0 *Contributors*: Evan from paris, france

File:Astrolabium Masha'allah Public Library Brugge Ms. 522.tif *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrolabium_Masha'allah_Public_Library_Brugge_Ms._522.tif *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Openbare Bibliotheek Brugge

File:Iranian Astrolabe 14.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Iranian_Astrolabe_14.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:M.safarniya

File:Yale's Hartmann astrolabe.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Yale's_Hartmann_astrolabe.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Ragesoss

File:Globe Celeste Louvre Asturlabi DSC 0713.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Globe_Celeste_Louvre_Asturlabi_DSC_0713.JPG *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Captainm

File:Planispheric astrolabe.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Planispheric_astrolabe.png *License*: Public Domain *Contributors*: Frb ds

File:Ballestilla.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Ballestilla.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Mcapdevila

File:Jacobstaff.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Jacobstaff.JPG *License*: Public Domain *Contributors*: Cherubino, Jljmt, Olve Utne

file:Commons-logo.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Commons-logo.svg *License*: logo *Contributors*: Anomie

File:Sphere filled blue.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sphere_filled_blue.svg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Geek3

File:latitude and longitude graticule on a sphere.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Latitude_and_longitude_graticule_on_a_sphere.svg *License*: Public Domain *Contributors*: Peter Mercator

File:December solstice geometry.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:December_solstice_geometry.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Peter Mercator

Image:MercNormSph enhanced.png *Source*: http://en.wikipedia.org/w/index.php?title=File:MercNormSph_enhanced.png *License*: Public Domain *Contributors*: Peter Mercator

Image:MercTranSph enhanced.png *Source*: http://en.wikipedia.org/w/index.php?title=File:MercTranSph_enhanced.png *License*: Public Domain *Contributors*: Peter Mercator

File:latitude and longitude graticule on an ellipsoid.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Latitude_and_longitude_graticule_on_an_ellipsoid.svg *License*: Public Domain *Contributors*: Peter Mercator

Image:Two-types-of-latitude.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Two-types-of-latitude.png *License*: Creative Commons Attribution 3.0 *Contributors*: Wmc824

File:Ellipsoid reduced angle definition.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Ellipsoid_reduced_angle_definition.svg *License*: Public Domain *Contributors*: Peter Mercator

Image:Types of latitude difference.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Types_of_latitude_difference.png *License*: GNU General Public License *Contributors*: User:Cburnett

File:Geodetic coordinates.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Geodetic_coordinates.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Peter Mercator

File:Geocentric coordinates.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Geocentric_coordinates.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Peter Mercator

File:Ellipsoidal coordinates.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Ellipsoidal_coordinates.svg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Peter Mercator

File:Longitude Vespucci.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Longitude_Vespucci.png *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Xiaphias. Original uploader was Xiaphias at en.wikipedia

File:John Harrison Uhrmacher.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:John_Harrison_Uhrmacher.jpg *License*: Public Domain *Contributors*: User:Simplicius

File:Longitude (PSF).png *Source*: http://en.wikipedia.org/w/index.php?title=File:Longitude_(PSF).png *License*: unknown *Contributors*: Gregors, Igno2, Inductiveload, KJG2007

File:Monuments of International Longitude Determination.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Monuments_of_International_Longitude_Determination.jpg *License*: Creative Commons Attribution-Share Alike *Contributors*: User:Mountain

File:Chronometer of Jeremy Thacker.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Chronometer_of_Jeremy_Thacker.jpg *License*: Public Domain *Contributors*: Anonynous 18th century

File:Hooke's reflecting instrument.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Hooke's_reflecting_instrument.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

File:Halley's-instrument.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Halley's-instrument.png *License*: GNU Free Documentation License *Contributors*: Michael Daly

File:Experienced sextant.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Experienced_sextant.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Michael Daly

File:Cercle de reflexion img 2600.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Cercle_de_reflexion_img_2600.jpg *License*: Creative Commons Attribution-Sharealike 2.0 *Contributors*: Photograph by Rama

File:Cercle-reflexion-Lenoir.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Cercle-reflexion-Lenoir.jpg *License*: GNU Free Documentation License *Contributors*: Karel K., Mcapdevila, Paris 16, Pline, Rama, Roomba, Wst

File:A mine of Iceland spar.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:A_mine_of_Iceland_spar.jpg *License*: Public Domain *Contributors*: Esben and the Witch

File:sunstone1.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sunstone1.jpg *License*: Public Domain *Contributors*: Original uploader was Donsimpson at en.wikipedia

File:sunstone2.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sunstone2.jpg *License*: Public Domain *Contributors*: Original uploader was Donsimpson at en.wikipedia

File:Labradoriteoregonsunstone.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Labradoriteoregonsunstone.jpg *License*: Public Domain *Contributors*: Astynax

File:William Burt Solar Compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:William_Burt_Solar_Compass.jpg *License*: Creative Commons Attribution 2.0 *Contributors*: Dustin Plunkett

File:Burt solar compass patent 1836.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Burt_solar_compass_patent_1836.jpg *License*: Public Domain *Contributors*: United States Patent Office - William Austin Burt inventor

File:Astrocompass mk II.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Astrocompass_mk_II.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: Mcapdevila

File:Kompas Sofia.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Kompas_Sofia.JPG *License*: GNU Free Documentation License *Contributors*: Bios, Homonihilis, Markscheider, Pymouss

File:Smartphone Compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Smartphone_Compass.jpg *License*: Creative Commons Zero *Contributors*: User:Zirguezi

File:Military Compass of J. Lindsay Brough.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Military_Compass_of_J._Lindsay_Brough.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Hannibal, John Andersson (WMSE), Markscheider

Image:Compass align.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Compass_align.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Shyamal

File:Model Si Nan of Han Dynasty.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Model_Si_Nan_of_Han_Dynasty.jpg *License*: GNU Free Documentation License *Contributors*: HéctorTabaré, Markscheider, Pymouss, Typo, Yug, 2 anonymous edits

File:Ming-marine-compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Ming-marine-compass.jpg *License*: Public Domain *Contributors*: Gisling, Man vyi, Stunteltje, 2 anonymous edits

File:Epistola-de-magnete.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Epistola-de-magnete.jpg *License*: Public Domain *Contributors*: Louis le Grand, Markscheider, Pymouss

File:Compass thumbnail.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Compass_thumbnail.jpg *License*: Public Domain *Contributors*: It Is Me Here, Liftarn, Mattes, Patrick87, Psychonaut, Roomba, Schimmelreiter, Wst, 2 anonymous edits

File:Kardanischer-Kompass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Kardanischer-Kompass.jpg *License*: Public Domain *Contributors*: Louis le Grand, Markscheider, Pymouss, Santosga

File:Bearing compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Bearing_compass.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: User:Inisheer

File:Flush mount compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Flush_mount_compass.jpg *License*: Public Domain *Contributors*: SoHome Jacaranda Lilau

File:Aero Magnetic Compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Aero_Magnetic_Compass.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Chopper

File:walkers compass arp.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Walkers_compass_arp.jpg *License*: Public Domain *Contributors*: Arpingstone, Markscheider, Pieter Kuiper, Pymouss

File:liquid filled compass.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Liquid_filled_compass.jpg *License*: Creative Commons Attribution-Sharealike 2.0 *Contributors*: Markscheider, Nikai, Pymouss

File:Cammenga-lensatic-compass-model-27.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Cammenga-lensatic-compass-model-27.jpg *License*: Creative Commons Attribution 3.0 *Contributors*: Siberex

File:Compasses orienteering.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Compasses_orienteering.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: User:Leinad

File:Brunton.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Brunton.JPG *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Qfl247 (talk) (Transferred by Citypeek/Original uploaded by Qfl247)

File:Boussole fantassin russe.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Boussole_fantassin_russe.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Jean-Patrick Donzey

File:MuseeMarine-compas-p1000468.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:MuseeMarine-compas-p1000468.jpg *License*: unknown *Contributors*: User:Rama

File:CompassUseMapMarked.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:CompassUseMapMarked.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Audrius Meskauskas

File:CompassUseTargetMarked.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:CompassUseTargetMarked.jpg *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: Audrius Meskauskas

File:Measuring azimuth with a compass.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Measuring_azimuth_with_a_compass.png *License*: Public Domain *Contributors*: US war department, United States government printing office (Washington)

File:MootHallSundial.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:MootHallSundial.JPG *License*: Public Domain *Contributors*: Wilson44691

File:Sundial-from-Marcianopolis.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sundial-from-Marcianopolis.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Edal Anton Lefterov

File:Tallinn, päikesekell.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Tallinn,_päikesekell.jpg *License*: unknown *Contributors*: User:Vamps

File:Equatorial sundial topview.gif *Source*: http://en.wikipedia.org/w/index.php?title=File:Equatorial_sundial_topview.gif *License*: Creative Commons Attribution 3.0 *Contributors*: WillowW

File:Sundial, Singapore Botanic Gardens.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sundial,_Singapore_Botanic_Gardens.jpg *License*: Creative Commons Attribution 2.0 *Contributors*: Michael Coghlan

File:Equation of time.svg *Source*: http://en.wikipedia.org/w/index.php?title=File:Equation_of_time.svg *License*: Creative Commons Attribution-Sharealike 2.5 *Contributors*: User:Drini, User:Zazou

File:Sundial in Supreme Court Gardens, Perth.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Sundial_in_Supreme_Court_Gardens,_Perth.jpg *License*: Public Domain *Contributors*: Dcoetzee

File:beijing sundial.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Beijing_sundial.jpg *License*: GNU Free Documentation License *Contributors*: User:Sputnikcccp

File:Garden sundial MN 2007.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Garden_sundial_MN_2007.JPG *License*: Creative Commons Attribution-ShareAlike 3.0 Unported *Contributors*: SEWilco

File:Houghton Hall Norfolk UK 4-face sundial.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Houghton_Hall_Norfolk_UK_4-face_sundial.jpg *License*: Creative Commons Attribution-Sharealike 3.0,2.5,2.0,1.0 *Contributors*: C.G. Mycock

File:Nové Město nad Metují sundials 2011 3.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Nové_Město_nad_Metují_sundials_2011_3.jpg *License*: Creative Commons Attribution 3.0 *Contributors*: Karelj

File:Verticalezonnewijzers-en.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Verticalezonnewijzers-en.jpg *License*: Public Domain *Contributors*: Original uploader was Willy Leenders at nl.wikipedia

File:RelSolValongo.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:RelSolValongo.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Gustavo F. Porto de Mello

File:Zw stelling.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Zw_stelling.jpg *License*: Creative Commons Attribution-Sharealike 2.5 *Contributors*: Original uploader was Willy Leenders at nl.wikipedia

File:Precision sundial in Bütgenbach-Belgium.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Precision_sundial_in_Bütgenbach-Belgium.jpg *License*: GNU Free Documentation License *Contributors*: Hoffmann Albin, www.precisionsundials.eu

File:Derby Sundial C 5810.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:Derby_Sundial_C_5810.JPG *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Clem Rutter, Rochester, Kent.

File:Ringsundial open.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Ringsundial_open.jpg *License*: Creative Commons Attribution-Sharealike 2.0 *Contributors*: jailbird

File:Zonnewijzerherkenrode.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Zonnewijzerherkenrode.jpg *License*: Public Domain *Contributors*: Willy Leenders

File:Tibetan Timestick.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Tibetan_Timestick.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Edmund Patrick, GeorgHH, Rama, Till.niermann

File:057Cracow.JPG *Source*: http://en.wikipedia.org/w/index.php?title=File:057Cracow.JPG *License*: Public Domain *Contributors*: Rj1979

File:Sundial solstice declination lines for different latitudes - slow.gif *Source*: http://en.wikipedia.org/w/index.php?title=File:Sundial_solstice_declination_lines_for_different_latitudes_-_slow.gif *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: User:Cmapm

File:Sundial in the form of a mandolin - Project Gutenberg eText 15050.png *Source*: http://en.wikipedia.org/w/index.php?title=File:Sundial_in_the_form_of_a_mandolin_-_Project_Gutenberg_eText_15050.png *License*: Public Domain *Contributors*: . Original uploader was Tagishsimon at en.wikipedia

File:Benoy sun clock.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Benoy_sun_clock.jpg *License*: Creative Commons Attribution-Sharealike 2.5 *Contributors*: British Sundial Society

File:Greenwich Royal Observatory Noon Mark.jpg *Source*: http://en.wikipedia.org/w/index.php?title=File:Greenwich_Royal_Observatory_Noon_Mark.jpg *License*: Creative Commons Attribution-Sharealike 3.0 *Contributors*: Christopher St J. H. Daniel

License

Creative Commons Attribution-Share Alike 3.0 Unported
//creativecommons.org/licenses/by-sa/3.0/