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# Advances in Navigation Map Our Future

## Animals Created with Genetically Engineered Homing Devices

Before Magellan circled the globe, before Alexander invaded Africa, even before our species painted the walls of caves, humankind and other animals had to find their way to hunting grounds and home again. Fortunately, knowing how essential navigation is to her many children, Mother Nature imbued most complex animals with numerous navigational tools, such as the built-in compasses of magnetite that she placed into the skulls of many migrators. Real-life shanghaied Lassies have traveled hundreds of miles to find their dog dishes again. Birds in covered boxes line up to face south in the fall and north in the spring. Aquatic creatures crowd a two-lane highway to reproduction, with salmon and shad scurrying up the very streams of their infanthood to spawn while mature Anguilla eels slide out of European and North America rivers toward precise romantic rendevous in the nebulous and meandering Sargasso Sea.

Humankind's honing of the art and science of navigation has proved crucial to our history, from the creation of our most powerful empires to the geographic discoveries of our greatest explorers, but today the subject often seems distant, historical, or so buried within our technological world that we take it for granted. Yet when the very word "naviga-tion" conjures only quaint images of nineteenth century captains with sextants raised, we would be advised to remember that navigational skills are actually more critical today than ever, whether we're trying to keep another *Exxon Valdez* from making love to a reef, preventing a thousand airborne jets from running into one another, or simply tracking a package being sent by UPS.

**The science of navigation often seems distant, historical, or so buried within our technological world that we take it for granted**

To find our way around the vast portions of the world with no signs or landmarks, like the oceans and skies, we must grapple with substantial challenges. We can "dead reckon" by keeping track of how fast we move for how long and in what direction. I first learned to navigate by looking over the side of a sailboat to judge the speed of the water moving by, following the swing of a compass, and plotting the boat's position on a paper chart. But because the fluid roads on which mariners and flyers travel themselves move at unknowable rates, a navigator's only reliable recourse is to triangulate his position using very distant known objects like the stars. In the mid-1970s, I was shooting the sun with a sextant and calculating my position thanks to spherical-geometry tables that were created so fast-moving aircraft during the Second World War could find their positions quickly. In two hundred years, except for a few fledgling and often inaccurate electronic devices, little had changed in the fundamental ways we naviga-tors found our way around. Today, however, we've entered a whole new era highly dependent on our electronically oriented world and the satellites that whirl around it. How did we get here and where are we going in the third millennium?

**(See 'The Ancients' on page 2)**

## ——— Finding Our Way ———

*Asymptote Review is now in its ninth year of publication, and during that time its subscription list has grown from a few hundred to over one thousand, five hundred. Of all the issues we have published, the first issue in 1998 generated by far the most reader response and interest. In it, we explored the validity of the old saying "necessity is the mother of invention" with the story of* **Steve Callahan**, *who in 1982 survived for 76 days alone in an inflatable raft after his sloop was rammed by some unknown object and sank near the Canary Islands. Before coming ashore eighteen-hundred miles away on a small Caribbean island, Callahan used ingenuity, bravery and incredible skill as a navigator to successfully plot his course to safety.*

*We recently asked Steve and his colleague,* **Kathy Massimini**, *if they would author an issue of Asymptote Review devoted to the history of navigation, and they graciously agreed. This issue will be of great interest not only to the pilot, hiker or sailor, but to anyone who is curious about how mankind learned to find his way about the Earth. We hope you enjoy it.*

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## In this issue

# The Ancients Sharpen Their Reading Skills

## History of Navigation
### At a Glance

### Ancient Navigation

circa 2500 B.C. New Guinea explorers begin to settle in Pacific Islands.

circa 1000 B.C. Vikings reach and settle Newfoundland, using an 8-point Norse compass.

circa 500 B.C. *Periplus* of Scylax, the oldest known pilot book, is used by Mediterranean navigators and develops into the portolean atlases of the Middle Ages.

384–322 B.C. Aristotle divides the horizon into a classical 8-wind system plus the solstitial points of sunrise and sunset.

circa 250 B.C. Eratosthenes accurately calculates the circumference of the earth.

2nd century B.C. Admiral Timosthenes of Rhodes designs a 12-point wind rose, naming the winds after the countries from which they blow.

190–120 B.C. Hipparchus of Nicaea catalogs stars on a circular sphere with celestial latitude and longitude, creating the astrolabe.

150 B.C. A large model of the globe, showing four land masses, is exhibited in Rome.

100 B.C. Eight-sided Tower of the Winds is erected in Athens, with emblems for Boreas (north), Kaikias (northeast), Burus (east), Apeliotes (southeast), Notos (south), Lips (southwest), Zephyrus (west), and Skiron (northwest).

85–165 A.D. Ptolemy maps the known world with coordinates of latitude and longitude.

(Continued from page 1)

No one knows how long Australian aborigines have traveled in accordance with their ancient "song lines," a complex method of integrating geographic features of the landscape with their history, spirituality, myths and music. We do think, however, that as long as 4,500 years ago, the peoples of Oceania began pushing out from New Guinea. By the time Magellan, Drake, and Cook found them, they had long ago settled the entire Pacific Basin without the benefit of compass or charts. Like the aborigines, these Pacific navigators learned to read natural landmarks, but theirs were more fluid than Australia's hills and deserts. At sea, clouds slow and build over islands. Creatures of the deep and air inhabit known regions of the oceans and travel along known migratory paths. Some birds hunt at sea but roost on land. Even the general patterns and specific shapes of multiple wave trains compose an intricate code that reveals predominant winds, distant storms, the strength and direction of current, and the bearing of land still well out of sight.

Perhaps the most important evolution in navigational expertise came as navigators shifted their gaze from terra firma to the heavens where the stars and planets never falter from their predictable patterns. The navigators of Oceania memorized these patterns so well that they could tell which stars would rise or set behind specific islands at different times of the year at different latitudes. The whole sky also became an ever-whirling compass. The skill of these navigators has become legend, but it is not pure art. In the early 1980's, mathematician Marvin Creamer extrapolated and codified their techniques so effectively that he sailed around the globe without the benefit of instruments.

The aborigines and Pacific islanders were not alone in tuning into the natural world. Ancient Norse mariners found land by following seabirds with beaks filled with fish. By the third millennium B.C., the Chinese had discovered the earth's magnetism and won a fog-bound battle thanks to a magnetized needle that pointed dutifully south. In the Mediterranean by 1000 B.C., Phoenicians created a maritime empire by tracking the sun, from Asu or sunrise (giving rise to the name Asia) in the east to Ereb or sunset (to evolve into Europe) to the west. Homer's *Odyssey* describes the importance of circumpolar starts to ancient navigators, and by 600 B.C., Thales of Miletos was teaching navigators to use Ursa Minor (the "Little Dipper") and the uniquely fixed north star (Polaris) around which all the heavens rotate. Still, Heredotus was among the many who, a couple centuries later, were still supplementing heavenly information with soundings of the ocean bottom and "ooze on the lead."

### Librarian Invents Leap Year & Calculates a Round World

In Africa and the Mediterranean, astronomy and geometry became the navigator's sharpening stone. Around 450 B.C., Oenopides discovered that the ecliptic, which defines the signs of the zodiac, lay at an angle of about 24 degrees from the celestial equator, indicating the earth's tilt on its axis. Eratosthenes, librarian of the great library of Alexandria, further refined celestial calculations, mapped 675 stars, and proposed a "leap day" in the calendar every four years to make sure the seasons would come out right. He also discovered that the sun shone straight down a well on one day of the year, so on that day he measured a 7.2-degree sun shadow down another well 787 miles north, allowing him to quite accurately calculate the circumference of a round earth some 1,742 years before Columbus sailed.

Spherical geometry also spawned virtually all future navigational inventions. Around 150 B.C., Hipparchus melded Babylonian math with Greek science to develop a spherical star chart with latitude and longitude coordinates. Flattened out, this became the astrolabe, a star computer and angle-measuring device. Eventually, mariner's astrolabes would become the standard shipboard tool carried by Magellan, Drake and Columbus.

At about the same time, the first world globe showing four land masses appeared in Rome. Claudius Ptolemy built upon his forebears' work in Alexandria during the first century A.D. His eight-volume *Geography* not only mapped the entire known world but also divided it into latitude and longitude, a system

(See 'Longitude' on page 3)

# Longitude, Latitude Discovered in First Century A.D.

## History of Navigation
### At a Glance

### From the Middle Ages to the Age of Empires and Enlightenment

| | |
|---|---|
| 1187 | Alexander Neckham, an English monk, records the first use of the compass by Europeans. |
| 1109 | Beatus map of Europe, Africa, and Asia (copied from a 776 map) includes a continent beyond the Red Sea. |
| circa 1290 | Pisa chart (oldest surviving sea chart) depicts two 16-point rhumb-line compasses. |
| 1270 | First recorded use of a sea chart as King Louis IX sails from Tunis on his last, ill-fated crusade. |
| 1310–1330 | Pietro Vesconte of Venice becomes the earliest known professional chart maker. |
| 1330 | Levi ben Gerson invents the cross staff |
| 14th century | Navigators move pegs on traverse boards every half hour to determine average course. |
| 1403–1483 | Lunar calendars allow navigators to calculate high tides. |
| 1420 | Prince Henry the Navigator establishes an academy at Sagres, Portugal. |
| 1480s | Portuguese formalize tables to determine latitude from the sun, and make globes. |
| 1481 | Mariner's astrolabe, made of wood and eventually cast in brass, is adopted. |
| 1489 | Cross-staff is first used at sea by Vasco da Gama, who also used the Arabian kamal. |
| 1500 | Juan de la Cosa develops one of the first charts of the world. |
| 1569 | Flemish map maker Gerard Mercator devises a solution to projecting the spherical earth on a flat surface. |

(Continued from page 2)

transposed on the earth from the heavenly globe surrounding it.

The earth, too, was divided into 360 degrees of longitude — 180 east and 180 west — and ringed by 90 degrees of latitude above and below the equator. Eventually, the nautical mile (6,076 feet) became the measure of a minute of arc (1/60 of a degree) at the equator, making much more geographic sense than the 5,280-foot statute mile. And since the earth rotates 360 degrees every 24 hours, navigators could equate time to arc — 15 degrees per hour or a mile every four seconds at the equator. They could calculate how far east or west they were from a reference point by "taking sights" or measuring the angles between the horizon and heavenly bodies, and then comparing those measurements to theoretical ones calculated for the reference point at the same time. Unfortunately, no one would be able to measure time accurately for centuries. Until then, navigators could only guesstimate their longitude and employ their astrolabes or similar devices to measure the altitude of Polaris. Polaris rests on the horizon at the equator—zero degrees of altitude at zero degrees latitude. At the north pole, or 90 degrees of latitude, Polaris stands at 90 degrees to the horizon. Knowing that Polaris indicates latitude fairly well, wayfarers would venture north or south to the same latitude as their destination, and then simply turn left or right and keep on trucking until they arrived.

### Age of Exploration Enlightens the Dark Ages

Throughout the middle ages, navigational advances seemed to languish. Around 1187, the compass appeared in Europe, and by the late 13th century, ships carried a magnetized needle fixed onto a compass card. (Previously, needles were inserted into straw and floated in a bowl of water, creating a the so-called "straw compass"). Also, by the late 1200s, charts had become standard fare, with Spanish and Italian maritime ordinances requiring them aboard all ships. Despite this handful of advances, it was not until 1420 when Prince Henry the Navigator of Portugal founded a school of navigation at Sagres that the field entered a whole new era in which techniques became codified and the invention of instruments blossomed. Henry was so successful that his tiny country became an enviable maritime powerhouse. Even Sir Francis Drake was only able to sail around the world after capturing a Portuguese navigator.

The marine astrolabe, which had been in use by 1481, was soon surpassed by the cross-staff, invented by Levi ben Gersen in 1330 but only first used at sea in 1498 by Vasco da Gama. Sighting down the staff, the navigator could slide along a short crossbar until one end of the bar appeared to touch the horizon and the other the star or sun. A graduated measure on the staff gave the angle, which decreased as the navigator slid the crossbar away from his eye. De Gama also used the Arabian kamal in a similar fashion. The kamal employed a simple square of wood as the crossbar and a string as the "staff." Neither invention was easy to use, especially when looking into the bright sun, so by 1595 navigators welcomed the backstaff, a more complex device that allowed navigators to turn away from the sun. Also aiding navigators came charts that more accurately depicted the globe. In 1500, Juan de la Cosa, who accompanied Columbus in 1492, produced one of the first world charts, but all map makers also remained challenged by longitude, the lines of which converge on the poles while latitude lines remain evenly spaced. To make accurate, flat maps, it took until 1569 before Flemish map maker Gerard Mercator learned to spread apart the latitude lines in proportion to the spreading of longitude lines as both distanced themselves from the equator. Although distorted—for example, Greenland appearing much larger than similar sized landmasses to the south—bearings remain consistent over an entire Mercator projection, so it remains today's standard for most maritime charts and land maps.

Even with greatly improved tools, however, mariners still faced grave dangers. On long voyages, they could time their speed using knotted lines paid out astern and estimate their distance run, but these were crude measuring devices. In addition, both currents and shifting magnetic variation of compasses made huge differences over a matter of days or weeks. Travelers simply could not tell how far east or west they had traveled. Charts also still proved wildly inaccurate, in part because longitudinal coordinates remained highly dubious. A system to accurately determine longitude

(See 'Rewards Spur' on page 4)

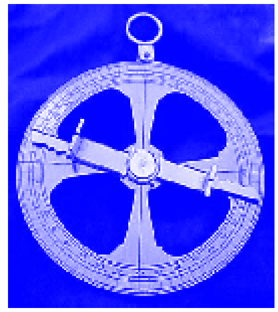
# Rewards spur further navigational inventions

## History of Navigation
### At a Glance

| | |
|---|---|
| 1582 | A map of the world includes Judgment, Purgatory, and the circles of Hell. |
| 1595 | Backstaff is described by John Davis in his *Seamans Secrets.* |
| 1701 | Edmund Halley publishes the first chart of worldwide magnetic variation. |
| 1731-1734 | John Hadley invents and patents the reflecting quadrant. |
| 1755 | Geography professor Tobias Mayer designs the first sextant. |
| 1765 | John Harrison builds his final chronometer, wins the longitude prize. |
| 1768 | Jesse Ramsden develops the first "dividing engine" sextant with accurate measures. |
| 1774 | Jean-Charles Borda invents the reflecting circle sextant, continuously used into the 20th century. |
| | Murdoch Mackenzie develops the station pointer for coastal surveying, used by James Cook. |
| 1816 | U.S. Coast and Geodetic Survey is organized to surveys of U.S. coast. |
| 1825 | Thomas Drummond's limelight, with parabolic mirrors, illuminates lighthouses. |
| 1830 | U.S. Hydrographic Office is established to study oceanography. |
| 1833 | U.S. Naval Observatory is founded to facilitate the laying of transatlantic cables. |
| 1850 | Hydrographic surveyors like Sir Frances Beaufort, William Henry Smyth, Captain Robert Fitzroy of HMS *Beagle*, have produced 2,000 nautical charts of the globe. |

**(Continued from page 3)**

became the navigator's Holy Grail. Finding it could literally spell the difference between an empire and a second-rate nation. So in 1567, Philip II of Spain offered prizes for anyone who succeeded—no one did—and established a royal observatory. In 1675, Charles II followed Philip's lead by founding the Royal Observatory at Greenwich, which on most maps today rests at zero degrees longitude. With the English empire at stake, Parliament offered a £20,000 prize in 1714 for a reliable system to find longitude, with £2,000 awards for other "worthy" navigational inventions.



What followed was a fascinating saga ranging, from the ridiculous to the sublime, so full of crony politics, professional jealousies and backbiting, and a single inventor's genius and fortitude that it led Dana Sobel's book on the subject, *Longitude,* to the *New York Times* best seller's list. Some of the high and mighty suggested idiotic systems, such as mooring ships across the Atlantic (in an average of 3,000+ feet of water!). The ships would shoot fireworks to let others track their positions. The truly learned, however, took more rational approaches. If navigators could accurately measure the position of the moon and planets in relation to the stars across which they moved, they could calculate time. In 1755, Tobias Mayer of Gottingen submitted lunar tables and a "reflecting circle" instrument to measure the moon's position. Unfortunately, the system proved too clumsy at sea, so Parliament rejected Mayer's claim to the prize. But the establishment, including Sir Isaac Newton, clung to celestial answers, so continued to snub theories of men like Genna Frisius, who had maintained in 1530 that the best answer was a reliable clock. Frisius's sixteenth century lacked the clock technology to handle the extreme changes in heat, humidity and motion found on ships. Even in the eighteenth, the longitudinal grail would become a 40-year quest for inventor and master clockmaker John Harrison.

Harrison had built clocks even of wood that remain reliable today. While he struggled to create the right mechanics without pendulums, he also finely tuned metalurgical components to balance the expansion of one material with the contraction of another. After five prototypes and countless mudfights with jealous bureaucrats, Harrison finally claimed the £20,000 prize, an equivalent of millions today.

Along with a reliable way to tell time, navigators now enjoyed greatly improved celestial protractors, which had previously been unable to measure large angles. In 1731, John Hadley had claimed a lesser prize for his reflecting quadrant (sometimes called an octant), which employed mirrors to allow the navigator to view both the horizon and a celestial body simultaneously, and to measure the angle very accurately. In 1757, Captain John Campbell directed John Bird to modify the quadrant to measure angles up to 120 degrees. The chronometer and reflecting sextant became the navigator's mainstay for two hundred years.

### Navigators Try to Figure Out What Wavelength They're On

The battle to control the seas generated the previous navigational revolution so it's no surprise that World War II issued in a new paradigm. James Clerk Maxwell predicted the electromagnetic spectrum in the 1860s, and Heinrich Hertz produced radio waves in 1887, but it took the war to inspire inventors to fully exploit the longer wavelengths and lower frequencies of the Hertzian band. Still reliant on geometry, they also built on experiments from 1920 and 1930s to usher humankind into the electronic era.

Radar bounced signals off distant objects and timed their return to determine range. Sonar and depth sounders mimicked the system underwater. Direction-finding radio-beacon stations sent out omnidirectional signals into which navigators could tune to obtain bearings. With two bearings navigators could get a "fix," but bearings proved highly inaccurate except when received quite close to the transmitters, so radio beacons proved most effective when navigators simply followed the signal to its source. Despite its limitations, similar direction-finding equipment has remained the primary flight-control system for air-traffic routing ever since. Loran (LOng RAnge Navigation, and its close-cousin DECCA), however, would become the most widely used and most precise navigational tools in the world by the early 1990s. Two or more Loran transmitters emanate a signal simultaneously. Receivers then note the difference in time

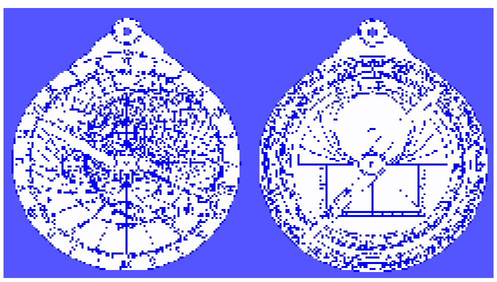
**(See 'Satellites' on page 5)**

# Satellites usher in latest age of discovery

(Continued from page 4)

between the reception of the two signals, producing a fix. The original units were as big as steamer trunks and required navigators to adjust and line up incoming sine waves, but computerization shrunk units to the size of a phone and automated reception. For the first time in history, travelers enjoyed push-button, near-instantaneous position fixes. But for all its wonder, Loran, too, suffered limitations. Although covering land and a few hundred miles offshore, Loran transmitters failed to reach much of the oceanic world and the skies above it. The final answer, once again, demanded that we look to the heavens.

In 1957, our family joined the entire neighborhood on our front lawns, eyes turned toward space. There it was: a slowly moving star. Sputnik. I could not have imagined that the navigational welfare of my adult life would develop from the fallout of that night when a cold war in space began. Researchers tracked Sputnik by measuring the Doppler shift in its emitted radio signal. It didn't take scientists long to realize that they could reverse the process, allowing a receiver to calculate a position on earth relative to a satellite along a known route. Within a decade, the U.S. government had launched 11 satellites as part of the SatNav navigation system for Polaris submarines, and released it for nonmilitary use. But receivers required multiple satellites for accuracy, and the satellites needed to pass at relatively steep angles to the receiver. Because the satellites were polar orbiting, a navigator at the equator might have to wait for almost two hours to get a fix. Still, for those of us still reliant upon sextants, SatNav was a miracle.



Not for long, however. Even before SatNav was in widespread use, the U.S. armed forces and Defense Mapping Agency proposed a refined satellite system that became known as GPS (Global Positioning System). With 11 satellites launched between 1978 and 1985, the system became an immediate success, quickly displacing Loran and SatNav. Today, with 24 GPS satellites orbiting at six altitudes, at least five satellites are "in view" at any time from anywhere in the world, giving very quick and extremely accurate positions. The positions were too good (as little as three to fifteen feet), at least from the military view. Afraid that enemies might utilize GPS for their own guidance systems, the U.S. government purposely degraded the signals for all but U.S. military navigators. It's not in humankind's nature to go backward, however. Soon the U.S. Coast Guard — yes, another branch of the federal government — was installing "differential GPS" stations to send Loran-style signals to GPS receivers to resharpen their accuracy. Thankfully, in 2000, the government finally regraded the signals they had degraded, making obsolete the multimillion dollar differential GPS system another part of the government had created — go figure.

Perhaps humankind hasn't proved itself the sharpest tool in the shed when pursuing its navigational goals, but today it's nearly impossible to get lost. It's true that many charts still in use are based on the original surveys by Captain Cook and others. Some islands in the Pacific, for instance, are mapped miles away from where they actually are. Generally, however, thanks to improved maps and satellite photos, our picture of the earth is now clear and complete. In addition, instruments accurately measure our speed through the air or water and over the ground plus our height in the air or depth in the sea. Radars have shrunk in size and cost until recreational boaters take them for granted. Thanks to the integration of homing signals and satellite technology, ELTs (Emergency Locator Transmitters, also called EPIRBs) bring rescuers directly to shipwrecked sailors, downed pilots, and injured hikers. And both GPS, and electronic mapping systems are appearing everywhere, often integrated with cellular communications, weather forecasting, and other technologies. Shipping and trucking companies now follow and direct their underway fleets to hone efficiencies. GPS and electronic mapping are standard gear in some cars already. In the not-distant future, a cyber-voice will direct you away from traffic jams or even slowdowns by integrating maps, GPS data, and information from highway sensors, allowing you to reach work or grandma's quickly. GPS bracelet-transmitters already reassure mothers at malls that they won't lose their children. Similar systems will likely track stolen cars or other lifted valuables on the way to the pawn shop. The paranoid may fear a future when we'll each have a transmitter installed within our heads at birth so Big Brother can keep an eye on us, but it's up to us to navigate around such science fiction nightmares with inventions that offer only exciting new frontiers.

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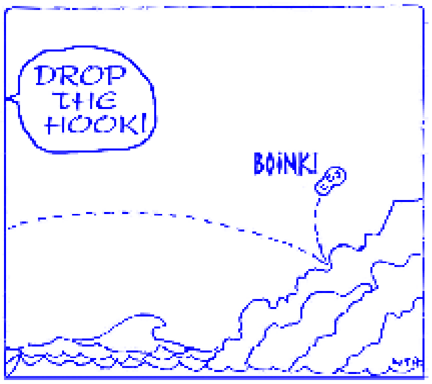
## History of Navigation
### At a Glance

### The Electromagnetic Revolution

| | |
|---|---|
| 1860s | James Clerk Maxwell, British physicist, predicts the electromagnetic spectrum. |
| 1884 | William Ferrel constructs an analog tide predictor. |
| 1887 | German physicist Heinrich Hertz produces the first communication radio waves. |
| 1915 | Alfred Wegener proposes continental drift from data collected by the HMS *Challenger* between 1872 and 1876. |
| 1925 | American physicists Gregory Breit and Merle Tuve use radio waves to detect distant objects, leading to Radar. |
| mid-1920s | Radiobeacons are developed. |
| 1930s | British, French, German, and American researchers develop experimental radar. |
| 1940 | DECCA becomes the radio-navigation system for much of the world. |
| 1940s | Loran-A is developed by the U.S. Defense Department. |
| late 1940s | Omega, with very long waves, is designed by U.S. Department of Defense for general worldwide navigation. |
| 1957 | *Sputnik* is launched by the Russians. |
| 1960s | U.S. Navy develops the Navy Navigation Satellite System (NNSS) for *Polaris* submarines. |
| 1967 | NNSS, also called Transit or Sat Nav, is released for nonmilitary use. |
| 1970s | Loran-C is developed to improve accuracy. |
| 1973–1985 | Global position system (GPS) is developed and becomes dominant nav system. |

# On the Lighter & Literary Side – Potato Navigation

If you get lost on the road, you can pull over, dig out a map, look for signs, or if all else fails, ask for directions. At sea, you're on your own to sort things out, and despite the efficacy of GPS and other modern navigational miracles, electronic reliability has proved more mythical than legendary. So mariners often fall back on common sense and simple methods of navigation that have worked for centuries if not millennia.




It is said that along the fog-shrouded, granite-toothed coast of Maine, sailors having no radar and, caught threading their way through flotillas of islands, have been known to revert to potato navigation. Simply put, the crew with the strongest arm stands on the bow, equipped with a large basket of Downeast spuds. Every once in awhile, the crew wings a potato forward. The boat continues to follow the sounds of splashing until there comes back through the fog a gentle thud. The pomme de terre, having found some terre in which to roost, signals the crew that it's time to drop the hook.

Such whimsical tools for finding one's way around are not far off the reality mark. David Burch's Emergency Navigation is a compendium of fundamental navigational skills, combining wisdom of the ages with modern-day inventiveness to teach you how to make a compass card out of a dinner plate, an AM radio into a direction finder, and a protractor out of your fingers, among other things. For the real skinny on how the ancients did it, tune into David Lewis's We the Navigators (Honolulu: University Press of Hawaii, 1972), a classic and scholarly work that details the methods used by real navigators who guided Lewis throughout the Pacific. Stephen Thomas's The Last Navigator (Camden, ME: International Marine Publishing, 1997) covers some of the same ground in a highlyreadable narrative about life in the islands. The following books will also enlighten those interested in the subject:

William J. H. Andrewes, ed., The Quest for Longitude, Boston: Harvard University Collection of Historical Scientific Instruments, 1993.

David Burch, Emergency Navigation, Camden, ME: International Marine Publishing, 1986.

Bonnie Dahl, The Users Guide to GPS, The Global Positioning System, Chicago: Richardsons' Marine Publishing, 1993.

Dava Sobel, Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time, New York: Penguin Books.

Peter Whitfield, The Charting of the Oceans, Ten Centuries of Maritime Maps, Rohnett Park, CA: Pomegrante Artbooks, 1996.

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