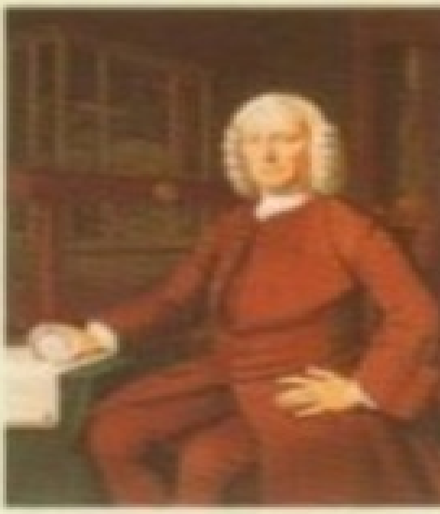
Longitude

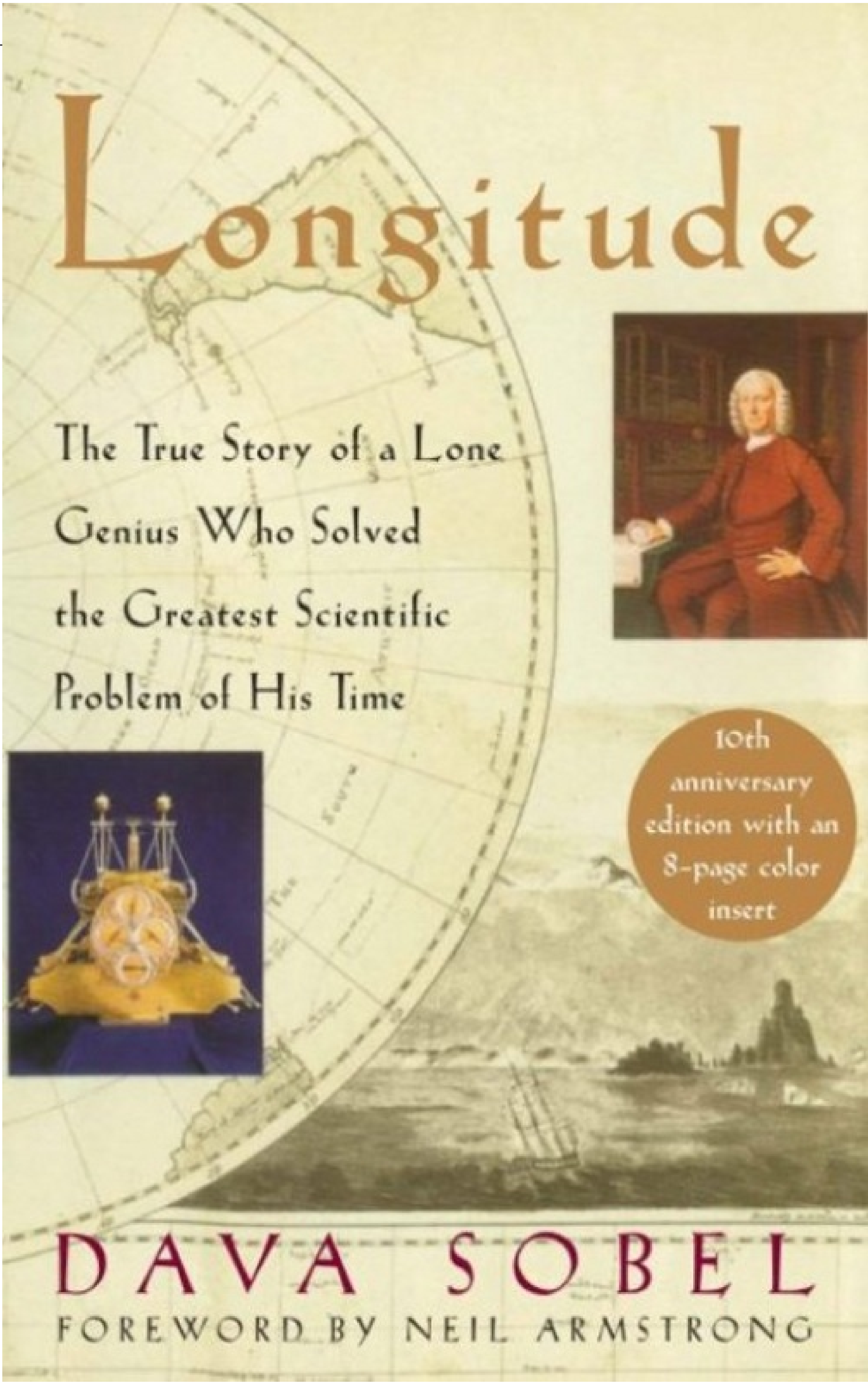


The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time

10th anniversary edition with an 8-page color insert

DAVA SOBEL

FOREWORD BY NEIL ARMSTRONG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LONGITUDE

The

True Story of a

Lone Genius

Who Solved

the Greatest

Scientific Problem

of His Time

DAVA SOBEL

Contents

For my mother,
Betty Gruber Sobel,
a four-star navigator
who can sail by the heavens
but always drives by way of Canarsie.

1.

Imaginary Lines

When I’m playful I use the meridians of longitude and parallels of latitude for a seine, drag the Atlantic Ocean for whales.

—MARK TWAIN, Life on the Mississippi

Once on a Wednesday excursion when I was a little girl, my father bought me a beaded wire ball tha I loved. At a touch, I could collapse the toy into a flat coil between my palms, or pop it open to make hollow sphere. Rounded out, it resembled a tiny Earth, because its hinged wires traced the same pattern of intersecting circles that I had seen on the globe in my schoolroom— the thin black lines of latitude and longitude. The few colored beads slid along the wire paths haphazardly, like ships on the high seas.

My father strode up Fifth Avenue to Rockefeller Center with me on his shoulders, and we stopped to stare at the statue of Atlas, carrying Heaven and Earth on his.

The bronze orb that Atlas held aloft, like the wire toy in my hands, was a see-through world, define by imaginary lines. The Equator. The Ecliptic. The Tropic of Cancer. The Tropic of Capricorn. The Arctic Circle. The prime meridian. Even then I could recognize, in the graph-paper grid imposed on the globe, a powerful symbol of all the real lands and waters on the planet.

Today, the latitude and longitude lines govern with more authority than I could have imagined forty-odd years ago, for they stay fixed as the world changes its configuration underneath them—wit continents adrift across a widening sea, and national boundaries repeatedly redrawn by war or peace.

As a child, I learned the trick for remembering the difference between latitude and longitude. The latitude lines, the *parallels*, really do stay parallel to each other as they girdle the globe from the Equator to the poles in a series of shrinking concentric rings. The meridians of longitude go the other way: They loop from the North Pole to the South and back again in great circles of the same size, so they all converge at the ends of the Earth.

Lines of latitude and longitude began crisscrossing our worldview in ancient times, at least three centuries before the birth of Christ. By A.D. 150, the cartographer and astronomer Ptolemy had plotte them on the twenty-seven maps of his first world atlas. Also for this landmark volume, Ptolemy liste all the place names in an index, in alphabetical order, with the latitude and longitude of each—as wel as he could gauge them from travelers’ reports. Ptolemy himself had only an armchair appreciation o the wider world. A common misconception of his day held that anyone living below the Equator would melt into deformity from the horrible heat.

The Equator marked the zero-degree parallel of latitude for Ptolemy. He did not choose it arbitrari but took it on higher authority from his predecessors, who had derived it from nature while observing the motions of the heavenly bodies. The sun, moon, and planets pass almost directly overhead at the Equator. Likewise the Tropic of Cancer and the Tropic of Capricorn, two other famous parallels, assume their positions at the sun's command. They mark the northern and southern boundaries of the sun's apparent motion over the course of the year.

Ptolemy was free, however, to lay his prime meridian, the zero-degree longitude line, wherever he liked. He chose to run it through the Fortunate Islands (now called the Canary & Madeira Islands) off the northwest coast of Africa. Later mapmakers moved the prime meridian to the Azores and to the Cape Verde Islands, as well as to Rome, Copenhagen, Jerusalem, St. Petersburg, Pisa, Paris, and Philadelphia, among other places, before it settled down at last in London. As the world turns, any line drawn from pole to pole may serve as well as any other for a starting line of reference. The placement of the prime meridian is a purely political decision.

Here lies the real, hard-core difference between latitude and longitude—beyond the superficial difference in line direction that any child can see: The zero-degree parallel of latitude is fixed by the laws of nature, while the zero-degree meridian of longitude shifts like the sands of time. This difference makes finding latitude child's play, and turns the determination of longitude, especially at sea, into an adult dilemma—one that stumped the wisest minds of the world for the better part of human history.

Any sailor worth his salt can gauge his latitude well enough by the length of the day, or by the height of the sun or known guide stars above the horizon. Christopher Columbus followed a straight path across the Atlantic when he "sailed the parallel" on his 1492 journey, and the technique would doubtless have carried him to the Indies had not the Americas intervened.

The measurement of longitude meridians, in comparison, is tempered by time. To learn one's longitude at sea, one needs to know what time it is aboard ship and also the time at the home port or another place of known longitude—at that very same moment. The two clock times enable the navigator to convert the hour difference into a geographical separation. Since the Earth takes twenty-four hours to complete one full revolution of three hundred sixty degrees, one hour marks one twenty-fourth of a spin, or fifteen degrees. And so each hour's time difference between the ship and the starting point marks a progress of fifteen degrees of longitude to the east or west. Every day at sea, when the navigator resets his ship's clock to local noon when the sun reaches its highest point in the sky, and then consults the home-port clock, every hour's discrepancy between them translates into another fifteen degrees of longitude.

Those same fifteen degrees of longitude also correspond to a distance traveled. At the Equator, where the girth of the Earth is greatest, fifteen degrees stretch fully one thousand miles. North or south of that line, however, the mileage value of each degree decreases. One degree of longitude equals four minutes of time the world over, but in terms of distance, one degree shrinks from sixty-eight miles at the Equator to virtually nothing at the poles.

Precise knowledge of the hour in two different places at once—a longitude prerequisite so easily accessible today from any pair of cheap wristwatches—was utterly unattainable up to and including the era of pendulum clocks. On the deck of a rolling ship, such clocks would slow down, or speed up, or stop running altogether. Normal changes in temperature encountered en route from a cold country of origin to a tropical trade zone thinned or thickened a clock's lubricating oil and made its metal parts expand or contract with equally disastrous results. A rise or fall in barometric pressure, or the subtle variations in the Earth's gravity from one latitude to another, could also cause a clock to gain or lose time.

For lack of a practical method of determining longitude, every great captain in the Age of Exploration became lost at sea despite the best available charts and compasses. From Vasco da Gama to Vasco Núñez de Balboa, from Ferdinand Magellan to Sir Francis Drake—they all got where they were going willy-nilly, by forces attributed to good luck or the grace of God.

As more and more sailing vessels set out to conquer or explore new territories, to wage war, or to ferry gold and commodities between foreign lands, the wealth of nations floated upon the oceans. An still no ship owned a reliable means for establishing her whereabouts. In consequence, untold numbe of sailors died when their destinations suddenly loomed out of the sea and took them by surprise. In a single such accident, on October 22, 1707, at the Scilly Isles near the southwestern tip of England, four homebound British warships ran aground and nearly two thousand men lost their lives.

The active quest for a solution to the problem of longitude persisted over four centuries and across the whole continent of Europe. Most crowned heads of state eventually played a part in the longitude story, notably King George III of England and King Louis XIV of France. Seafaring men such as Captain William Bligh of the *Bounty* and the great circumnavigator Captain James Cook, who made three long voyages of exploration and experimentation before his violent death in Hawaii, took the more promising methods to sea to test their accuracy and practicability.

Renowned astronomers approached the longitude challenge by appealing to the clockwork univers Galileo Galilei, Jean Dominique Cassini, Christiaan Huygens, Sir Isaac Newton, and Edmond Halley, of comet fame, all entreated the moon and stars for help. Palatial observatories were founded at Paris London, and Berlin for the express purpose of determining longitude by the heavens. Meanwhile, lesser minds devised schemes that depended on the yelps of wounded dogs, or the cannon blasts of signal ships strategically anchored—somehow—on the open ocean.

In the course of their struggle to find longitude, scientists struck upon other discoveries that changed their view of the universe. These include the first accurate determinations of the weight of t Earth, the distance to the stars, and the speed of light.

As time passed and no method proved successful, the search for a solution to the longitude probler assumed legendary proportions, on a par with discovering the Fountain of Youth, the secret of perpetual motion, or the formula for transforming lead into gold. The governments of the great maritime nations— including Spain, the Netherlands, and certain city-states of Italy—periodically roiled the fervor by offering jackpot purses for a workable method. The British Parliament, in its famed Longitude Act of 1714, set the highest bounty of all, naming a prize equal to a king’s ransom (several million dollars in today’s currency) for a “Practicable and Useful” means of determining longitude.

English clockmaker John Harrison, a mechanical genius who pioneered the science of portable precision timekeeping, devoted his life to this quest. He accomplished what Newton had feared was impossible: He invented a clock that would carry the true time from the home port, like an eternal flame, to any remote corner of the world.

Harrison, a man of simple birth and high intelligence, crossed swords with the leading lights of his day. He made a special enemy of the Reverend Nevil Maskelyne, the fifth astronomer royal, who contested his claim to the coveted prize money, and whose tactics at certain junctures can only be described as foul play.

With no formal education or apprenticeship to any watchmaker, Harrison nevertheless constructed series of virtually friction-free clocks that required no lubrication and no cleaning, that were made from materials impervious to rust, and that kept their moving parts perfectly balanced in relation to one another, regardless of how the world pitched or tossed about them. He did away with the pendulum, and he combined different metals inside his works in such a way that when one componen expanded or contracted with changes in temperature, the other counteracted the change and kept the clock's rate constant.

His every success, however, was parried by members of the scientific elite, who distrusted Harrison's magic box. The commissioners charged with awarding the longitude prize—Nevil Maskelyne among them—changed the contest rules whenever they saw fit, so as to favor the chances of astronomers over the likes of Harrison and his fellow "mechanics." But the utility and accuracy of Harrison's approach triumphed in the end. His followers shepherded Harrison's intricate, exquisite invention through the design modifications that enabled it to be mass produced and enjoy wide use.

An aged, exhausted Harrison, taken under the wing of King George III, ultimately claimed his rightful monetary reward in 1773—after forty struggling years of political intrigue, international warfare, academic backbiting, scientific revolution, and economic upheaval.

All these threads, and more, entwine in the lines of longitude. To unravel them now—to retrace their story in an age when a network of orbiting satellites can nail down a ship's position within a few feet in just a moment or two—is to see the globe anew.

2.

The Sea Before Time

They that go down to the Sea in Ships, that do business in great waters, these see the works of the Lord, and His wonders in the deep.

—Psalm 107

Dirty weather," Admiral Sir Clowdisley Shovell called the fog that had dogged him twelve days at sea. Returning home victorious from Gibraltar after skirmishes i with the French Mediterranean forces, Sir Clowdisley could not beat the heavy autumn overcast. Fearing the ships might founder on coastal rocks, the admiral summoned all his navigators to put their heads together.

The consensus opinion placed the English fleet safely west of Île d'Ouessant, an island outpost of the Brittany peninsula. But as the sailors continued north, they discovered to their horror that they ha misgauged their longitude near the Scilly Isles. These tiny islands, about twenty miles from the southwest tip of England, point to Land's End like a path of steppingstones. And on that foggy night October 22, 1707, the Scillies became unmarked tombstones for almost two thousand of Sir Clowdisley's troops.

The flagship, the *Association*, struck first. She sank within minutes, drowning all hands. Before the rest of the vessels could react to the obvious danger, two more ships, the *Eagle* and the *Romney*, pricked themselves on the rocks and went down like stones. In all, four of the five warships were lost

Only two men washed ashore alive. One of them was Sir Clowdisley himself, who may have watched the fifty-seven years of his life flash before his eyes as the waves carried him home. Certainly he had time to reflect on the events of the previous twenty-four hours, when he made what must have been the worst mistake in judgment of his naval career. He had been approached by a sailo a member of the *Association*'s crew, who claimed to have kept his own reckoning of the fleet's location during the whole cloudy passage. Such subversive navigation by an inferior was forbidden i the Royal Navy, as the unnamed seaman well knew. However, the danger appeared so enormous, by his calculations, that he risked his neck to make his concerns known to the officers. Admiral Shovell had the man hanged for mutiny on the spot.

No one was around to spit "I told you so!" into Sir Clowdisley's face as he nearly drowned. But as soon as the admiral collapsed on dry sand, a local woman combing the beach purportedly found his body and fell in love with the emerald ring on his finger. Between her desire and his depletion, she handily murdered him for it. Three decades later, on her deathbed, this same woman confessed the crime to her clergyman, producing the ring as proof of her guilt and contrition.

The demise of Sir Clowdisley's fleet capped a long saga of seafaring in the days before sailors could find their longitude. Page after page from this miserable history relates quintessential horror stories of death by scurvy and thirst, of ghosts in the rigging, and of landfalls in the form of shipwrecks, with hulls dashed on rocks and heaps of drowned corpses fouling the beaches. In literally hundreds of instances, a vessel's ignorance of her longitude led swiftly to her destruction.

Launched on a mix of bravery and greed, the sea captains of the fifteenth, sixteenth, and seventeenth centuries relied on “dead reckoning” to gauge their distance east or west of home port. The captain would throw a log overboard and observe how quickly the ship receded from this temporary guidepost. He noted the crude speedometer reading in his ship’s logbook, along with the direction of travel, which he took from the stars or a compass, and the length of time on a particular course, counted with a sandglass or a pocket watch. Factoring in the effects of ocean currents, fickle winds, and errors in judgment, he then determined his longitude. He routinely missed his mark, of course—searching in vain for the island where he had hoped to find fresh water, or even the continen that was his destination. Too often, the technique of dead reckoning marked him for a dead man.

Long voyages waxed longer for lack of longitude, and the extra time at sea condemned sailors to th dread disease of scurvy. The oceangoing diet of the day, devoid of fresh fruits and vegetables, deprived them of vitamin C, and their bodies’ connective tissue deteriorated as a result. Their blood vessels leaked, making the men look bruised all over, even in the absence of any injury. When they were injured, their wounds failed to heal. Their legs swelled. They suffered the pain of spontaneous hemorrhaging into their muscles and joints. Their gums bled, too, as their teeth loosened. They gaspe for breath, struggled against debilitating weakness, and when the blood vessels around their brains ruptured, they died.

Beyond this potential for human suffering, the global ignorance of longitude wreaked economic havoc on the grandest scale. It confined oceangoing vessels to a few narrow shipping lanes that promised safe passage. Forced to navigate by latitude alone, whaling ships, merchant ships, warships and pirate ships all clustered along well-trafficked routes, where they fell prey to one another. In 159 for example, a squadron of six English men-of-war coasted off the Azores, lying in ambush for Spanish traders heading back from the Caribbean. The *Madre de Deus*, an enormous Portuguese galleon returning from India, sailed into their web. Despite her thirty-two brass guns, the *Madre de Deus* lost the brief battle, and Portugal lost a princely cargo. Under the ship’s hatches lay chests of gold and silver coins, pearls, diamonds, amber, musk, tapestries, calico, and ebony. The spices had to be counted by the ton— more than four hundred tons of pepper, forty-five of cloves, thirty-five of cinnamon, and three each of mace and nutmeg. The *Madre de Deus* proved herself a prize worth half million pounds sterling—or approximately half the net value of the entire English Exchequer at that date.

By the end of the seventeenth century, nearly three hundred ships a year sailed between the British Isles and the West Indies to ply the Jamaica trade. Since the sacrifice of a single one of these cargo vessels caused terrible losses, merchants yearned to avoid the inevitable. They wished to discover secret routes—and that meant discovering a means to determine longitude.

The pathetic state of navigation alarmed the renowned English diarist Samuel Pepys, who served f a time as an official of the Royal Navy. Commenting on his 1683 voyage to Tangiers, Pepys wrote: “ is most plain, from the confusion all these people are in, how to make good their reckonings, even each man’s with itself, and the nonsensical arguments they would make use of to do it, and disorder they are in about it, that it is by God’s Almighty Providence and great chance, and the wideness of th sea, that there are not a great many more misfortunes and ill chances in navigation than there are.”

That passage appeared prescient when the disastrous wreck on the Scillies scuttled four warships. The 1707 incident, so close to the shipping centers of England, catapulted the longitude question into the forefront of national affairs. The sudden loss of so many lives, so many ships, and so much honor all at once, on top of centuries of previous privation, underscored the folly of ocean navigation without a means for finding longitude. The souls of Sir Clowdisley's lost sailors— another two thousand martyrs to the cause—precipitated the famed Longitude Act of 1714, in which Parliament promised a prize of £20,000 for a solution to the longitude problem.

In 1736, an unknown clockmaker named John Harrison carried a promising possibility on a trial voyage to Lisbon aboard H.M.S. *Centurion*. The ship's officers saw firsthand how Harrison's clock could improve their reckoning. Indeed, they thanked Harrison when his newfangled contraption showed them to be about sixty miles off course on the way home to London.

By September 1740, however, when the *Centurion* set sail for the South Pacific under the comman of Commodore George Anson, the longitude clock stood on terra firma in Harrison's house at Red Lion Square. There the inventor, having already completed an improved second version of it, was har at work on a third with further refinements. But such devices were not yet generally accepted, and would not become generally available for another fifty years. So Anson's squadron took the Atlantic the old-fashioned way, on the strength of latitude readings, dead reckoning, and good seamanship. Th fleet reached Patagonia intact, after an unusually long crossing, but then a grand tragedy unfolded, founded on the loss of their longitude at sea.

On March 7, 1741, with the holds already stinking of scurvy, Anson sailed the *Centurion* through the Straits Le Maire, from the Atlantic into the Pacific Ocean. As he rounded the tip of Cape Horn, a storm blew up from the west. It shredded the sails and pitched the ship so violently that men who los their holds were dashed to death. The storm abated from time to time only to regather its strength, an punished the *Centurion* for fifty-eight days without mercy. The winds carried rain, sleet, and snow. And scurvy all the while whittled away at the crew, killing six to ten men every day.

Anson held west against this onslaught, more or less along the parallel at sixty degrees south latitude, until he figured he had gone a full two hundred miles westward, beyond Tierra del Fuego. Th other five ships of his squadron had been separated from the *Centurion* in the storm, and some of the were lost forever.

On the first moonlit night he had seen in two months, Anson at last anticipated calm waters, and steered north for the earthly paradise called Juan Fernández Island. There he knew he would find fres water for his men, to soothe the dying and sustain the living. Until then, they would have to survive o hope alone, for several days of sailing on the vast Pacific still separated them from the island oasis. But as the haze cleared, Anson sighted *land* right away, dead ahead. It was Cape Noir, at the western edge of Tierra del Fuego.

How could this have happened? Had they been sailing in reverse?

The fierce currents had thwarted Anson. All the time he thought he was gaining westward, he had been virtually treading water. So he had no choice but to head west *again*, then north toward salvatio He knew that if he failed, and if the sailors continued dying at the same rate, there wouldn't be enoug hands left to man the rigging.

According to the ship's log, on May 24, 1741, Anson at last delivered the *Centurion* to the latitude of Juan Fernandez Island, at thirty-five degrees south. All that remained to do was to run down the parallel to make harbor. But which way should he go? Did the island lie to the east or to the west of the *Centurion*'s present position?

That was anybody's guess.

Anson guessed west, and so headed in that direction. Four more desperate days at sea, however, stripped him of the courage of his conviction, and he turned the ship around.

Forty-eight hours after the *Centurion* began beating east along the thirty-fifth parallel, land was sighted! But it showed itself to be the impermeable, Spanish-ruled, mountain-walled coast of Chile. This jolt required a one-hundred-eighty-degree change in direction, and in Anson's thinking. He was forced to confess that he had probably been within hours of Juan Fernandez Island when he abandone west for east. Once again, the ship had to retrace her course.

On June 9, 1741, the *Centurion* dropped anchor at last at Juan Fernandez. The two weeks of zigzag searching for the island had cost Anson an additional eighty lives. Although he was an able navigator who could keep his ship at her proper depth and protect his crew from mass drowning, his delays had given scurvy the upper hand. Anson helped carry the hammocks of sick sailors ashore, then watched helplessly as the scourge picked off his men one by one . . . by one by one, until more than half of the original five hundred were dead and gone.

3.

Adrift in a Clockwork Universe

One night I dreamed I was locked in my Father's watch
With Ptolemy and twenty-one ruby stars
Mounted on spheres and the Primum Mobile
And the notched spheres eating each other's rinds
To the last tooth of time, and the case closed.

—JOHN CIARDI, "My Father Watch"

As Admiral Shovell and Commodore Anson showed, even the best sailors lost their bearings once they lost sight of land, for the sea offered no useful clue about longitude. The sky, however, held out hope. Perhaps there was a way to read longitude in the relative positions of the celestial bodies.

The sky turns day to night with a sunset, measures the passing months by the phases of the moon, and marks each season's change with a solstice or an equinox. The rotating, revolving Earth is a cog a clockwork universe, and people have told time by its motion since time began.

When mariners looked to the heavens for help with navigation, they found a combination compass and clock. The constellations, especially the Little Dipper with the North Star in its handle, showed them where they were going by night—provided, of course, the skies were clear. By day, the sun not only gave direction but also told them the time if they followed its movements. So they watched it ris orange out of the ocean in the east, change to yellow and to blinding white as it gained altitude, until at midday the sun stopped in its tracks—the way a ball tossed in the air pauses momentarily, poised between ascent and descent. That was the noon siren. They set their sand-glasses by it every clear day Now all they needed was some astronomical event to tell them the time somewhere else. If, for example, a total lunar eclipse was predicted for midnight over Madrid, and sailors bound for the Wes Indies observed it at eleven o'clock at night their time, then they were one hour earlier than Madrid, and therefore fifteen degrees of longitude west of that city.

Solar and lunar eclipses, however, occurred far too rarely to provide any meaningful aid to navigation. With luck, one could hope to get a longitude fix once a year by this technique. Sailors needed an everyday heavenly occurrence.

As early as 1514, the German astronomer Johannes Werner struck on a way to use the motion of th moon as a location finder. The moon travels a distance roughly equal to its own width every hour. At night, it appears to walk through the fields of fixed stars at this stately pace. In the daytime (and the moon is up in the daytime for half of every month) it moves toward or away from the sun.

Werner suggested that astronomers should map the positions of the stars along the moon's path an predict when the moon would brush by each one—on every moonlit night, month to month, for years to come. Also the relative positions of the sun and moon through the daylight hours should be similarly mapped. Astronomers could then publish tables of all the moon's meanderings, with the time of each star meeting predicted for one place—Berlin, perhaps, or Nuremberg—whose longitude would serve as the zero-degree reference point. Armed with such information, a navigator could compare the time he observed the moon near a given star with the time the same conjunction was supposed to occur in the skies over the reference location. He would then determine his longitude by finding the difference in hours between the two places, and multiplying that number by fifteen degrees.

The main problem with this "lunar distance method" was that the positions of the stars, on which the whole process depended, were not at all well known. Then, too, no astronomer could predict exactly where the moon would be from one night or day to the next, since the laws that governed the moon's motion still defied detailed understanding. And besides, sailors had no accurate instruments for measuring moon-to-star distances from a rolling ship. The idea was way ahead of its time. The quest for another cosmic time cue continued.

In 1610, almost one hundred years after Werner's immodest proposal, Galileo Galilei discovered from his balcony in Padua what he thought was the sought-after clock of heaven. As one of the first t turn a telescope to the sky, Galileo encountered an embarrassment of riches there: mountains on the moon, spots on the sun, phases of Venus, a ring around Saturn (which he mistook for a couple of close-set moons), and a family of four satellites orbiting the planet Jupiter the way the planets orbit the sun. Galileo later named these last the Medicean stars. Having thus used the new moons to curry political favor with his Florentine patron, Cosimo de' Medici, he soon saw how they might serve the seaman's cause as well as his own.

Galileo was no sailor, but he knew of the longitude problem—as did every natural philosopher of his day. Over the next year he patiently observed the moons of Jupiter, calculating the orbital periods of these satellites, and counting the number of times the small bodies vanished behind the shadow of the giant in their midst. From the dance of his planetary moons, Galileo worked out a longitude solution. Eclipses of the moons of Jupiter, he claimed, occurred one thousand times annually—and so predictably that one could set a watch by them. He used his observations to create tables of each satellite's expected disappearances and reappearances over the course of several months, and allowed himself dreams of glory, foreseeing the day when whole navies would float on his timetables of astronomical movements, known as ephemerides.

Galileo wrote about his plan to King Philip III of Spain, who was offering a fat life pension in ducats to "the discoverer of longitude." By the time Galileo submitted his scheme to the Spanish court, however, nearly twenty years after the announcement of the prize in 1598, poor Philip had been worn down by crank letters. His staff rejected Galileo's idea on the grounds that sailors would be hard-pressed just to see the satellites from their vessels—and certainly couldn't hope to see them often enough or easily enough to rely on them for navigation. After all, it was never possible to view the hands of the Jupiter clock during daylight hours, when the planet was either absent from the sky o overshadowed by the sun's light. Nighttime observations could be carried on for only part of the year and then only when skies were clear.

In spite of these obvious difficulties, Galileo had designed a special navigation helmet for finding longitude with the Jovian satellites. The headgear—the *celatone*—has been compared to a brass gas mask in appearance, with a telescope attached to one of the eyeholes. Through the empty eyehole, the observer's naked eye could locate the steady light of Jupiter in the sky. The telescope afforded the other eye a look at the planet's moons.

An inveterate experimenter, Galileo took the contraption out on the harbor of Livorno to demonstrate its practicability. He also dispatched one of his students to make test runs aboard a ship, but ~~the method never gained adherents. Galileo himself conceded that, even on land, the pounding~~ of one’s heart could cause the whole of Jupiter to jump out of the telescope’s field of view.

Nevertheless, Galileo tried to peddle his method to the Tuscan government and to officials in the Netherlands, where other prize money lay unclaimed. He did not collect any of these funds, although the Dutch gave him a gold chain for his efforts at cracking the longitude problem.

Galileo stuck to his moons (now rightly called the Galilean satellites) the rest of his life, followin them faithfully until he was too old and too blind to see them any longer. When Galileo died in 1642, interest in the satellites of Jupiter lived on. Galileo’s method for finding longitude at last became generally accepted after 1650—but only on land. Surveyors and cartographers used Galileo’s technique to redraw the world. And it was in the arena of mapmaking that the ability to determine longitude won its first great victory. Earlier maps had underestimated the distances to other continen and exaggerated the outlines of individual nations. Now global dimensions could be set, with authority, by the celestial spheres. Indeed, King Louis XIV of France, confronted with a revised map of his domain based on accurate longitude measurements, reportedly complained that he was losing more territory to his astronomers than to his enemies.

The success of Galileo’s method had mapmakers clamoring for further refinements in predicting eclipses of the Jovian satellites. Greater precision in the timing of these events would permit greater exactitude in charting. With the borders of kingdoms hanging in the balance, numerous astronomers found gainful employment observing the moons and improving the accuracy of the printed tables. In 1668, Giovanni Domenico Cassini, a professor of astronomy at the University of Bologna, published the best set yet, based on the most numerous and most carefully conducted observations. Cassini’s well-wrought ephemerides won him an invitation to Paris to the court of the Sun King.

Louis XIV, despite any disgruntlement about his diminishing domain, showed a soft spot for science. He had given his blessing to the founding, in 1666, of the French Académie Royale des Sciences, the brainchild of his chief minister, Jean Colbert. Also at Colbert’s urging, and under the ever-increasing pressure to solve the longitude problem, King Louis approved the building of an astronomical observatory in Paris. Colbert then lured famous foreign scientists to France to fill the ranks of the Académie and man the observatory. He imported Christiaan Huygens as charter membe of the former, and Cassini as director of the latter. (Huygens went home to Holland eventually and traveled several times to England in relation to his work on longitude, but Cassini grew roots in France and never left. Having become a French citizen in 1673, he is remembered as a French astronomer, so that his name today is given as Jean-Dominique as often as Giovanni Domenico.)

From his post at the new observatory, Cassini sent envoys to Denmark, to the ruins of Uranienborg the “heavenly castle” built by Tycho Brahe, the greatest naked-eye astronomer of all time. Using observations of Jupiter’s satellites taken at these two sites, Paris and Uranienborg, Cassini confirme the latitude and longitude of both. Cassini also called on observers in Poland and Germany to cooperate in an international task force devoted to longitude measurements, as gauged by the motion of Jupiter’s moons.

It was during this ferment of activity at the Paris Observatory that visiting Danish astronomer Ole Roemer made a startling discovery: The eclipses of all four Jovian satellites would occur ahead of schedule when the Earth came closest to Jupiter in its orbit around the sun. Similarly, the eclipses fel behind the predicted schedules by several minutes when the Earth moved farthest from Jupiter. Roemer concluded, correctly, that the explanation lay in the velocity of light. The eclipses surely occurred with sidereal regularity, as astronomers claimed. But the time that those eclipses could be observed on Earth depended on the distance that the light from Jupiter's moons had to travel across space.

Until this realization, light was thought to get from place to place in a twinkling, with no finite velocity that could be measured by man. Roemer now recognized that earlier attempts to clock the speed of light had failed because the distances tested were too short. Galileo, for example, had tried i vain to time a light signal traveling from a lantern on one Italian hilltop to an observer on another. H never detected any difference in speed, no matter how far apart the hills he and his assistants climbed But in Roemer's present, albeit inadvertent, experiment, Earthbound astronomers were watching for the light of a moon to reemerge from the shadow of another world. Across these immense interplanetary distances, significant differences in the arrival times of light signals showed up. Roemer used the departures from predicted eclipse times to measure the speed of light for the first time in 1676. (He slightly underestimated the accepted modern value of 300,000 kilometers per second.)

In England, by this time, a royal commission was embarked on a wild goose chase—a feasibility study of finding longitude by the dip of the magnetic compass needle on seagoing vessels. King Charles II, head of the largest merchant fleet in the world, felt the urgency of the longitude problem acutely, and desperately hoped the solution would sprout from his soil. Charles must have been pleased when his mistress, a young Frenchwoman named Louise de Keroualle, reported this bit of news: One of her countrymen had arrived at a method for finding longitude and had himself recently arrived from across the Channel to request an audience with His Majesty. Charles agreed to hear the man out.

The Frenchman, the sieur de St. Pierre, frowned on the moons of Jupiter as a means of determinin longitude, though they were all the rage in Paris. He put his personal faith in the guiding powers of Earth's moon, he said. He proposed to find longitude by the position of the moon and some select sta —much as Johannes Werner had suggested one hundred sixty years previously. The king found the idea intriguing, so he redirected the efforts of his royal commissioners, who included Robert Hooke, polymath equally at home behind a telescope or a microscope, and Christopher Wren, architect of St. Paul's Cathedral.

For the appraisal of St. Pierre's theory, the commissioners called in the expert testimony of John Flamsteed, a twenty-seven-year-old astronomer. Flamsteed's report judged the method to be sound i theory but impractical in the extreme. Although some passing fair observing instruments had been developed over the years, thanks to Galileo's influence, there was still no good map of the stars and known route for the moon.

Flamsteed, with youth and pluck on his side, suggested that the king might remedy this situation b establishing an observatory with a staff to carry out the necessary work. The king complied. He also appointed Flamsteed his first personal "astronomical observator"— a title later changed to astronom royal. In his warrant establishing the Observatory at Greenwich, the king charged Flamsteed to apply "the most exact Care and Diligence to rectifying the Tables of the Motions of the Heavens, and the Places of the fixed Stars, so as to find out the so-much desired Longitude at Sea, for perfecting the ar of Navigation."

In Flamsteed's own later account of the turn of these events, he wrote that King Charles "certainly did not want his ship-owners and sailors to be deprived of any help the Heavens could supply, whereb navigation could be made safer."

Thus the founding philosophy of the Royal Observatory, like that of the Paris Observatory before i viewed astronomy as a means to an end. All the far-flung stars must be cataloged, so as to chart a course for sailors over the oceans of the Earth.

Commissioner Wren executed the design of the Royal Observatory. He set it, as the king's charter decreed, on the highest ground in Greenwich Park, complete with lodging rooms for Flamsteed and one assistant. Commissioner Hooke directed the actual building work, which got under way in July o 1675 and consumed the better part of one year.

Flamsteed took up residence the following May (in a building still called Flamsteed House today) and collected enough instruments to get to work in earnest by October. He toiled at his task for more than four decades. The excellent star catalog he compiled was published posthumously in 1725. By then, Sir Isaac Newton had begun to subdue the confusion over the moon's motion with his theory of gravitation. This progress bolstered the dream that the heavens would one day reveal longitude.

Meanwhile, far from the hilltop haunts of astronomers, craftsmen and clockmakers pursued an alternate path to a longitude solution. According to one hopeful dream of ideal navigation, the ship's captain learned his longitude in the comfort of his cabin, by comparing his pocket watch to a constan clock that told him the correct time at home port.

4.

Time in a Bottle

There being no mystic communion of clocks
it hardly matters when this autumn breeze
wheeled down from the sun
to make leaves skirt pavement like a
million lemmings.
An event is such a little piece of time-and-space
you can mail it through the slotted eye of the cat.

—DIANE ACKERMAN, “Mystic Communion of Clocks”

Time is to clock as mind is to brain. The clock or watch somehow contains the time. And yet time refuses to be bottled up like a genie stuffed in a lamp. Whether it flows as sand or turns on wheels within wheels, time escapes irretrievably, while we watch. Even when the bulbs of the hourglass shatter, when darkness withholds the shadow from the sundial, when the mainspring winds down so far that the clock hands hold still as death, time itself keeps on. The most we can hope a watch to do i mark that progress. And since time sets its own tempo, like a heartbeat or an ebb tide, timepieces don’t really keep time. They just keep up with it, if they’re able.

Some clock enthusiasts suspected that good timekeepers might suffice to solve the longitude problem, by enabling mariners to carry the home-port time aboard ship with them, like a barrel of water or a side of beef. Starting in 1530, Flemish astronomer Gemma Frisius hailed the mechanical clock as a contender in the effort to find longitude at sea.

“In our times we have seen the appearance of various small clocks, capably constructed, which, for their modest dimensions, provide no problem to those who travel,” Frisius wrote. He must have mean they provided no problem of heft or high price to rich travelers; certainly they did not keep time very well. “And it is with their help that the longitude can be found.” The two conditions that Frisius spelled out, however— namely, that the clock be set to the hour of departure with “the greatest exactness” and that it not be allowed to run down during the voyage—virtually ruled out any chance applying the method at that time. The clocks of the early sixteenth century weren’t equal to the task. They were neither accurate nor able to run true against the assault of changing temperature on the hig seas.

Although it is not clear whether he knew of Gemma Frisius’s suggestion, William Cunningham of England revived the timekeeper idea in 1559, recommending watches “such as are brought from Flanders” or found “without Temple barre,” right in London, for the purpose. But these watches typically gained or lost as many as fifteen minutes a day, and thus fell far short of the accuracy required to determine one’s whereabouts. (Multiplying a difference in hours by fifteen degrees gives only an approximation of location; one also needs to divide the number of minutes and seconds by four, to convert the time readings to degrees and minutes of arc.) Nor had timepieces enjoyed any significant advances by 1622, when English navigator Thomas Blundeville proposed using “some tru Horologie or Watch” to determine longitude on transoceanic voyages.

The shortcomings of the watch, however, failed to squelch the dream of what it might do once perfected.

Galileo, who, as a young medical student, successfully applied a pendulum to the problem of takin pulses, late in life hatched plans for the first pendulum clock. In June of 1637, according to Galileo’s protégé and biographer, Vincenzo Viviani, the great man described his idea for adapting the pendulur “to clocks with wheelwork for assisting the navigator to determine his longitude.”

Legends of Galileo recount an early mystical experience in church that fostered his profound insights about the pendulum as timekeeper: Mesmerized by the to-and-fro of an oil lamp suspended from the nave ceiling and pushed by drafts, he watched as the sexton stopped the pan to light the wic Rekindled and released with a shove, the chandelier began to swing again, describing a larger arc this time. Timing the motion of the lamp by his own pulse, Galileo saw that the length of a pendulum determines its rate.

Galileo always intended to put this remarkable observation to work in a pendulum clock, but he never got around to building one. His son, Vincenzio, constructed a model from Galileo’s drawings, and the city fathers of Florence later built a tower clock predicated on that design. However, the distinction for completing the first working pendulum clock fell to Galileo’s intellectual heir, Christiaan Huygens, the landed son of a Dutch diplomat who made science his life.

Huygens, also a gifted astronomer, had divined that the “moons” Galileo observed at Saturn were really a *ring*, impossible as that seemed at the time. Huygens also discovered Saturn’s largest moon, which he named Titan, and was the first to notice markings on Mars. But Huygens couldn’t be tied to the telescope all the time. He had too many other things on his mind. It is even said that he chided Cassini, his boss at the Paris Observatory, for the director’s slavish devotion to daily observing.

Huygens, best known as the first great horologist, swore he arrived at the idea for the pendulum clock independently of Galileo. And indeed he evinced a deeper understanding of the physics of pendulum swings—and the problem of keeping them going at a constant rate—when he built his first pendulum-regulated clock in 1656. Two years later Huygens published a treatise on its principles, called the *Horologium,* in which he declared his clock a fit instrument for establishing longitude at sea.

By 1660, Huygens had completed not one but two marine timekeepers based on his principles. He tested them carefully over the next several years, sending them off with cooperative sea captains. On the third such trial, in 1664, Huygens’s clocks sailed to the Cape Verde Islands, in the North Atlantic off the west coast of Africa, and kept good track of the ship’s longitude all the way there and back.

Now a recognized authority on the subject, Huygens published another book in 1665, the *Kort Onderwys*, his directions for the use of marine timekeepers. Subsequent voyages, however, exposed a certain finickiness in these machines. They seemed to require favorable weather to perform faithfully The swaying of the ship on a storm’s waves confounded the normal swinging of the pendulum.

To circumvent this problem, Huygens invented the spiral balance spring as an alternative to the pendulum for setting a clock’s rate, and had it patented in France in 1675. Once again, Huygens foun himself under pressure to prove himself the inventor of a new advance in timekeeping, when he met a hot-blooded and headstrong competitor in the person of Robert Hooke.

Hooke had already made several memorable names for himself in science. As a biologist studying the microscopic structure of insect parts, bird feathers, and fish scales, he applied the word *cell* to describe the tiny chambers he discerned in living forms. Hooke was also a surveyor and builder who helped reconstruct the city of London after the great fire of 1666. As a physicist, Hooke had his hand in fathoming the behavior of light, the theory of gravity, the feasibility of steam engines, the cause of earthquakes, and the action of springs. Here, in the coiled contrivance of the balance spring, Hooke clashed with Huygens, claiming the Dutchman had stolen his concept.

The Hooke-Huygens conflict over the right to an English patent for the spiral balance spring disrupted several meetings of the Royal Society, and eventually the matter was dropped from the minutes, without being decided to either contestant's satisfaction.

In the end, there was no end to the strife, though neither Hooke nor Huygens produced a true marin timekeeper. The separate failures of these two giants seemed to dampen the prospects for ever solvin the longitude problem with a clock. Disdainful astronomers, still struggling to amass the necessary data required to employ their lunar distance technique, leaped at the chance to renounce the timekeeper approach. As far as they could see, the answer would come from the heavens—from the clockwork universe and not from any ordinary clock.

Powder of Sympathy

The College will the whole world measure;
Which most impossible conclude,
And Navigation make a pleasure
By finding out the Longtitude.
Every Tarpaulin shall then with ease
Sayle any ship to the Antipodes.

—ANONYMOUS (ABOUT 1660) "Ballad of Gresham College"

At the end of the seventeenth century, even as members of learned societies debated the means to a longitude solution, countless cranks and opportunists published pamphlets to promulgate their own harebrained schemes for finding longitude at sea.

Surely the most colorful of the offbeat approaches was the wounded dog theory, put forth in 1687. was predicated on a quack cure called powder of sympathy. This miraculous powder, discovered in southern France by the dashing Sir Kenelm Digby, could purportedly heal at a distance. All one had t do to unleash its magic was to apply it to an article from the ailing person. A bit of bandage from a wound, for example, when sprinkled with powder of sympathy, would hasten the closing of that wound. Unfortunately, the cure was not painless, and Sir Kenelm was rumored to have made his patients jump by powdering—for medicinal purposes—the knives that had cut them, or by dipping their dressings into a solution of the powder.

The daft idea to apply Digby's powder to the longitude problem follows naturally enough to the prepared mind: Send aboard a wounded dog as a ship sets sail. Leave ashore a trusted individual to di the dog's bandage into the sympathy solution every day at noon. The dog would perforce yelp in reaction, and thereby provide the captain a time cue. The dog's cry would mean, "the Sun is upon the Meridian in London." The captain could then compare that hour to the local time on ship and figure the longitude accordingly. One had to hope, of course, that the powder really held the power to be fel many thousand leagues over the sea, and yet—and this is very important—fail to heal the telltale wound over the course of several months. (Some historians suggest that the dog might have had to be injured more than once on a major voyage.)

Whether this longitude solution was intended as science or satire, the author points out that submitting "a Dog to the misery of having always a Wound about him" is no more macabre or mercenary than expecting a seaman to put out his own eye for the purposes of navigation. "[B]efore the Back-Quadrants were Invented," the pamphlet states, "when the Forestaff was most in use, there was not one Old Master of a Ship amongst Twenty, but what a Blind in one Eye by daily staring in th Sun to find his Way." This was true enough. When English navigator and explorer John Davis introduced the backstaff in 1595, sailors immediately hailed it as a great improvement over the old cross-staff, or Jacob's staff. The original sighting sticks had required them to measure the height of the sun above the horizon by looking directly into its glare, with only scant eye protection afforded b the darkened bits of glass on the instruments' sighting holes. A few years of such observations were enough to destroy anyone's eyesight. Yet the observations had to be made. And after all those early navigators lost at least half their vision finding the latitude, who would wince at wounding a few wretched dogs in the quest for longitude?

A much more humane solution lay in the magnetic compass, which had been invented in the twelft century and become standard equipment on all ships by this time. Mounted on gimbals, so that it remained upright regardless of the ship's position, and kept inside a binnacle, a stand that supported and protected it from the elements, the compass helped sailors find direction when overcast skies obscured the sun by day or the North Star at night. But the combination of a clear night sky and a goo compass *together*, many seamen believed, could also tell a ship's longitude. For if a navigator could read the compass and see the stars, he could get his longitude by splitting the distance between the tw north poles—the magnetic and the true.

The compass needle points to the magnetic north pole. The North Star, however, hovers above the actual pole—or close to it. As a ship sails east or west along any given parallel in the northern hemisphere, the navigator can note how the distance between the magnetic and the true pole changes At certain meridians in the mid-Atlantic the intervening distance looks large, while from certain Pacific vantage points the two poles seem to overlap. (To make a model of this phenomenon, stick a whole clove into a navel orange, about an inch from the navel, and then rotate the orange slowly at ey level.) A chart could be drawn—and many were—linking longitude to the observable distance between magnetic north and true north.

This so-called magnetic variation method had one distinct advantage over all the astronomical approaches: It did not depend on knowing the time at two places at once or knowing when a predicte event would occur. No time differences had to be established or subtracted from one another or multiplied by any number of degrees. The relative positions of the magnetic pole and the Pole Star sufficed to give a longitude reading in degrees east or west. The method seemingly answered the dream of laying legible longitude lines on the surface of the globe, except that it was incomplete and inaccurate. Rare was the compass needle that pointed precisely north at all times; most displayed some degree of variation, and even the variation varied from one voyage to the next, making it tough to get precise measurements. What's more, the results were further contaminated by the vagaries of terrestrial magnetism, the strength of which waxed or waned with time in different regions of the sea as Edmond Halley found during a two-year voyage of observation.

In 1699, Samuel Fyler, the seventy-year-old rector of Stockton, in Wiltshire, England, came up wi a way to draw longitude meridians on the night sky. He figured that he—or someone else more verse in astronomy—could identify discrete rows of stars, rising from the horizon to the apex of the heavens. There should be twenty-four of these star-spangled meridians, or one for each hour of the day. Then it would be a simple matter, Fyler supposed, to prepare a map and timetable stating when each line would be visible over the Canary Islands, where the prime meridian lay by convention in those days. The sailor could observe the row of stars above his head at local midnight. If it were the fourth, for argument's sake, and his tables told him the first row should be over the Canaries just the assuming he had some knowledge of the time, he could figure his longitude as three hours—or forty-five degrees—west of those islands. Even on a clear night, however, Fyler's approach invoked more astronomical data than existed in all the world's observatories, and its reasoning was as circular as th celestial sphere.

Admiral Shovell's disastrous multishipwreck on the Scilly Isles after the turn of the eighteenth