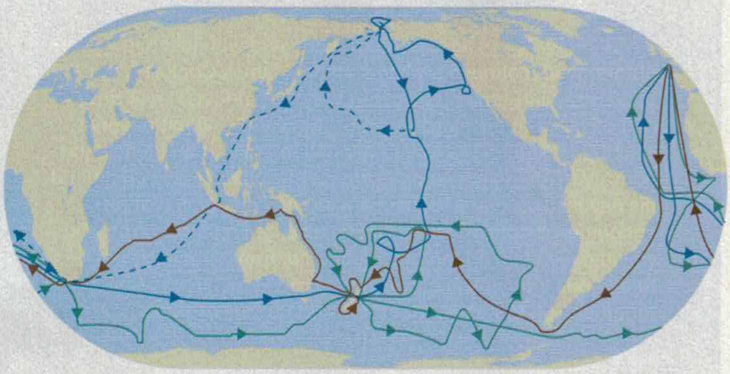

▲ **VOYAGES OF EXPLORATION** Cook's first, second, and third voyages are shown in brown, green, and blue, respectively. The dotted blue line shows his ship's voyage home after Cook was killed in Hawaii.

Magellan's fleet between 1519 and 1522, his estimate of the longitude of the Philippines was off by 53 degrees, or approximately 3,500 miles.

In 1612, two years after he discovered Jupiter's four bright satellites, Galileo realized that their regular motions could serve as a "universal clock" for determining longitude. In 1668 the great Italian-French astronomer Giovanni Domenico Cassini published accurate tables of the positions of Jupiter's satellites, which were used to improve maps of Europe. The timing of other predictable astronomical events such as solar eclipses, lunar eclipses, and occultations of bright stars by the Moon could also be used, but they aren't frequent enough to be practical.

Observing Jupiter's satellites is problematic because it requires a stably mounted telescope. That's fine when observing from land but problematic aboard a ship. What was needed was a predictable astronomical event that happened frequently and could be observed accurately at sea. In 1514 the German mathematician Johannes Werner suggested using the distance between the Moon and the Sun or other reference star for determining longitude. The Moon's orbital motion causes it to move through the background stars at 13.2° per day, or 33′ per hour. So if the distance between the Moon and a known star can be measured accurate to, say, 3.3′, that determines the time — and hence the longitude — within six minutes, which is six nautical miles at the equator.

Unfortunately, unlike Jupiter's satellites, which are far from the Sun and strongly bound to their massive planet, the Moon is attracted roughly equally by Earth and the Sun, making its motion very complex. Only in 1755 did the German astronomer Tobias Mayer come up with a way to compute the Moon's orbit sufficiently accurately to be useful for the lunar distance method.

The other alternative was to use a mechanical clock set to Greenwich Time. By the mid-1700s the best pendulum clocks had achieved an accuracy of a few minutes per year, but only if mounted on a stable platform. At the time of Cook's first voyage (1768 to 1771), the only clock that could keep accurate time at sea was John Harrison's H4 chronometer, which was unavailable because it was being evaluated for the Longitude Prize set up by the British Parliament in 1714.

But Harrison's H4 clock was only expected to provide accurate time during the two-month trip from Britain to the West Indies; its cumulative error would have made it almost useless for Cook's multiyear voyages.

For his first voyage Cook used lunar distances as his primary method for determining Greenwich Time. He measured the angular distance between the Moon and the Sun or reference star with a sextant, and recorded the local time. He consulted the *British Nautical Almanac* to determine at what time the angular distance would be the same if observed from Greenwich.

Although the lunar distance method is simple in concept, other factors make it more complex in practice. Atmospheric refraction causes the Moon and the star to appear higher than they actually are. The Moon is also close enough to Earth that its apparent position must be adjusted for parallax. So in addition to obtaining the angular distance between the Moon and the star, it's necessary to measure the altitudes of the two objects above the horizon, as shown on page 62. Applying the corrections for refraction and parallax (called *clearing*) requires the use of spherical trigonometry. To simplify the computations, mathematicians developed a clever method using logarithms. This operation didn't require the

◀ **THE ONCE AND FUTURE SEXTANT** Sextants use mirrors to superpose the images of two distinct objects, much as rangefinders in old-fashioned cameras do. The angle between the objects can then be read off a finely calibrated scale. In 2016 the U.S. Navy reemphasized training with sextants, because they are immune to antisatellite weapons, electromagnetic pulses, and hacking.