Engineering the Heavens

Pre-photographic astronomers first measured the distances to stars using their eyeballs, thanks to superb engineering by astronomical instrument-makers

by **Trudy E. Bell**

GLANCE UP on a clear starlit night, and the stars seem stationary in their constellations—no wonder for millennia they were even called "fixed" stars, reassuringly useful as aids to terrestrial navigation and surveying. But careful observers from the 17th through the 19th Centuries vigilantly monitored the positions of stars night after night, year after year, decade after decade. They discovered that all those points of light have their own motions in three dimensions—away or towards the earth, across the sky, around one another—all in the invisible thrall of gravity.

In so doing, they also unexpectedly discovered important physical motions of the earth itself, distinguishable from individual stellar motions because the effects were of the wrong magnitude, frequency, or direction, or (the ultimate tip-off) affected all the stars in the sky.

In that pre-photographic era, astronomers measured the movements of the stars using their eyeballs, looking through specialized telescopes of only a few inches aperture. Unlike a regular telescope, basically consisting of a tube with a mirror or lens at one end and an eyepiece at the other on a sturdy movable mount, the emphasis was not only on the optics—and not at all on making the mirror or lens as big as possible to gather light from faint objects deep in space for hand-drawing their physical appearance. Instead, these single-purpose instruments of precision (as they came to be called) were sometimes not even recognizable as astronomical instruments: their telescope tubes were possibly fixed in one position or perhaps obscured by frames, wheels, clamps, microscopes, handles, circles with numbers, bubble levels, plumb bobs, small pools of mercury, or lanterns for illuminating crosshairs made from spiderweb [Fig. 1].

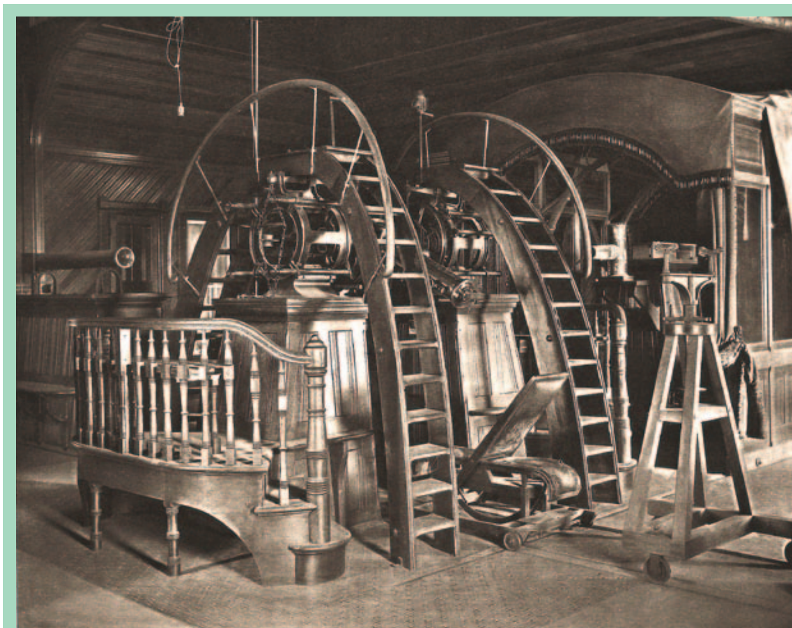

Fig. 1. This 6.4-inch meridian circle by the German instrument makers Adolf and Georg Repsold, installed at the Lick Observatory on Mount Hamilton, CA, in 1884, is almost unrecognizable as an astronomical instrument. The telescope, half-hidden near the center of the image above the half-reclined couch (for the observer to see stars near the zenith), is fixed on an east-west axis rotating in pivots atop the two wood-encased piers. A meridian circle was used to measure the altitude and hour angle of stars crossing the meridian (the vertical plane through astronomical north and the observer's zenith). To quantify instrumental errors and responses to changes in temperature and other ambient conditions, between astronomical observations the meridian circle is calibrated with collimating telescopes such as the one at far left. It is also frequently reversed 180 degrees in the pivots. The reversing apparatus is the odd tripod-like device at the right. Note the tapestry and wooden shelter at right, drawn on rails over the instrument when not in use. [Credit: Richard H. Tucker, *Meridian Circle Observations of 310 Standard Stars.* Publications of the Lick Observatory. Volume IV. 1900.]

All the finely counterbalanced machinery may have even been invented for a specific astronomical task, and was built by optical and mechanical artisans who came to be as famous as the astronomers who used their handiwork.

Who Cared?

Through the exquisite engineering of English and German (and to a lesser extent French and American) astronomical instrument makers, visual positional astronomy came to reign as the "Xtreme Science" of the 19th Century, so effective that visual observing techniques persisted into the 20th Century.

One big quest, which drove astronomers for nearly three centuries, was a race to determine annual stellar parallax—empirical verification of the Copernican hypothesis that the earth orbits the sun, as well as actual measurement of the

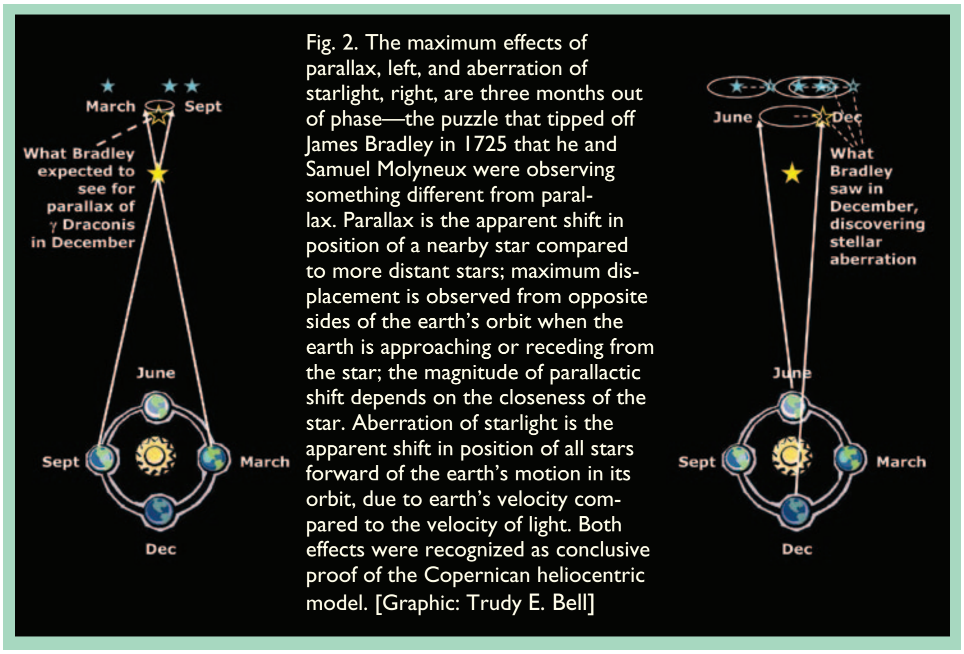

Fig. 2. The maximum effects of parallax, left, and aberration of starlight, right, are three months out of phase—the puzzle that tipped off James Bradley in 1725 that he and Samuel Molyneux were observing something different from parallax. Parallax is the apparent shift in position of a nearby star compared to more distant stars; maximum displacement is observed from opposite sides of the earth's orbit when the earth is approaching or receding from the star; the magnitude of parallactic shift depends on the closeness of the star. Aberration of starlight is the apparent shift in position of all stars forward of the earth's motion in its orbit, due to earth's velocity compared to the velocity of light. Both effects were recognized as conclusive proof of the Copernican heliocentric model. [Graphic: Trudy E. Bell]

gulf yawning between us and a nearby star.

The concept of parallax is simple: surveyors call the technique triangulation. As the earth moves around the sun, a closer star observed first from one side of the earth's orbit and then, six months later, from the opposite side, should appear to shift position back and forth compared to more distant stars. The magnitude of the parallactic shift would depend on the star's distance from the earth: closer stars should display a larger annual parallax than farther ones.

No Scientific Proof

When Nicholas Copernicus died in 1543 and left the world his deliberately posthumous magnum opus *De Revolutionibus Orbium Coelestium (On the Revolution of the Celestial Spheres)*, hypothesizing a heliocentric planetary system, he had no scientific proof that the earth orbits the sun. Indeed, he was incorrect in sticking to the Aristotelian concept that planets followed perfectly circular orbits centered on the sun. Over the next 180 years, Johannes Kepler derived three mathematical laws that described planetary orbits as ellipses with the sun at one focus; Galileo first turned a telescope skyward and observed that Venus went through phases similar to the phases of the moon that were readily explainable if Venus orbited the sun; and Isaac Newton showed (among other things) that Kepler's laws and elliptical orbits were explained by universal gravitational attraction among masses. These and other major developments gave a heliocentric system physical street cred, so to speak; well into the 18th Century, however, the motion of the earth around the sun had not been empirically verified by direct observation (the annual parade of the constellations notwithstanding).

Most Newtonians felt that lack of detectable parallax was due to the extreme distance of the stars; by 1718, Edmond Halley (yes, later famous for predicting the return of what we now call Halley's Comet), calculated that based on the best measurements up to then, the fixed stars had to be at least 20,000 to 30,000 times farther than the sun. In short, the lack of detectable parallax was an instrumental issue, which (to use modern language) simply put a lower bound on the closeness of stars. There was only one way to find out: build instruments precise enough to allow detection. But how good did such measuring instruments need to be?

First, a brief crash course on small-angle positional astronomy essentials for engineers.

Since time immemorial, visual astronomers have measured—and still measure—celestial angles in the very non-metric/non-SI system of degrees, minutes, and seconds of arc. (Radio astronomers also use radians, but radio astronomy was founded by electrical engineers.) There are, of course, 360 degrees in the full celestial sphere, 180 from horizon through the zenith to horizon. A degree is about twice the diameter of the full moon. An arcminute is 1/60th of a degree (take it up with the Babylonians). An arcsecond is 1/60th of an arcminute.

The arcsecond is so important to positional astronomers that it's worth dwelling here more than, well, a second. How small is a second of arc? Introductory astronomy books are full of unhelpful comparisons such as it's the angle subtended by a dime at about 2.5 miles, or a third of a millimeter at the length of a football field. Here's an astronomically meaningful comparison of my own: if the moon (which is 2,140 miles across) subtends an angle of about 0.5 degree, then 1 arcsec is roughly 1/1,800th the diameter of the moon—about 1.2 miles at the distance of the lunar orbit.

Thus, an angle of 0.1 arcsec—positional astronomy territory that became accessible to pre-photographic visual observers in the 19th Century through instruments of precision—represents a distance of just 0.12 mile or 627 feet across on the moon. Put another way, to an imaginary positional astronomer on the moon looking back at the earth, measuring an angle of 0.1 arcsec at the distance of the earth would mean pinpointing the distance between the Washington Monument in Washington, DC., and Caesar's Palace in Las Vegas, Nevada, to an accuracy of a city block.

Celestial Motions

In 1725, wealthy British amateur astronomer Samuel Molyneux contacted George Graham, an eminent London clockmaker credited with (among other inventions) the deadbeat clock escapement, the mercury compensated pendulum, the orrery, and the precision micrometer screw, which allowed him to devise calipers and other measuring instruments of unparalleled accuracy. Molyneux commissioned Graham to build a new type of astronomical instrument called a zenith sector: a telescope of less than 4 inches aperture but 24¼ feet long, installed vertically on the wall of Molyneux's chimney in his mansion in Kew. The tube was suspended from a pivot near the top so it could move through only a slight angle, simply to measure differences in the north-south positions of stars as the rotation of the earth caused stars to drift from east to west overhead.

Molyneux asked Oxford University professor of astronomy James Bradley to help carefully measure the position

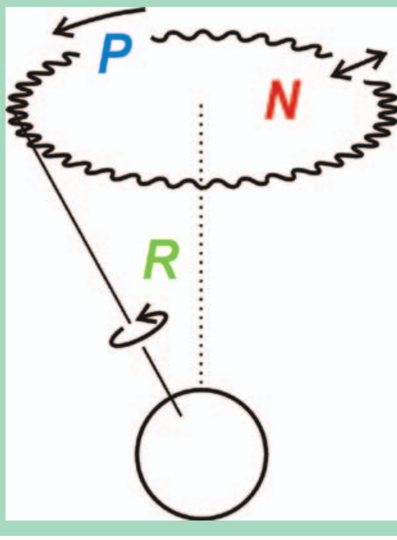

Fig. 3a, right, shows the earth's rotational axis (R) sweeping a large circle in the sky in about 26,000 years, radically changing the direction of astronomical north; this precession (P) was known even to the ancient Greeks. Nutation (N), is a nodding oscillation of precession, discovered by James Bradley in the mid-18th Century. Both effects are due to the gravitational effect of the Sun and the Moon on the earth's equatorial bulge, and affect the positions of all the stars in the sky. Cool fact: Nutation also changes the latitude of the Tropics of Cancer and Capricorn on the earth, as shown in Fig. 3b, above. Markers beside the Zaragoza-Victoria road in northern Mexico denote the drift. [Credits: Diagram: Dr. H. Sulzer, Photo: Roberto González.]

of Gamma Draconis, the brightest star in the constellation Draco (despite being designated with the third letter of the Greek alphabet gamma or γ) that passed almost directly through the zenith of London. Over several nights in December 1725, to their amazement, Molyneux and Bradley measured γ Draconis passing increasingly south of its anticipated position; over the next few months, it slowly returned north, reaching a maximum northerly position in June 1726 about 40 arcsecs north of its most southerly extent.

Baffled because the direction and timing of the star's movements were three months out of phase from what would have been expected from annual parallax in the direction of that star [Fig. 2], in 1727 Bradley commissioned Graham to build another zenith sector, which could pivot through an angle of 6¾ degrees on either side of the zenith, so as to observe some 200 stars throughout the year. After extensive testing, Bradley was confident the new zenith sector could detect angles as small as 0.5 arcsec.

After observing that other stars also traced out little circles or ellipses of the identical magnitude (diameter or major axis of about 40 arcsecs), Bradley had an epiphany about the cause. The star positions were displaced due to the combination of the motion of the earth in its orbit (about 18 miles or 30 km per second) and the speed of the light from the star (about 186,000 miles or 300,000 km per second), an effect he called the aberration of starlight. The position of each star in the sky is slightly displaced forward of the earth's direction of movement; the little circles or ellipses were a projection of the plane of the earth's orbit toward that star's direction in the sky. The aberration of starlight was itself an unexpected definitive empirical proof that the earth indeed orbits the sun—indeed, the first empirical verification of the Copernican heliocentric model. Although no one had yet measured the speed of light, discrepancies in the timings of the eclipses of Jupiter's moons from different positions in the earth's orbit had already shown that the speed of light was finite; from angular measurements of stellar aberration, Bradley calculated that the earth's orbital velocity had to be 1/10,210th the speed of light—accurate to about one percent.

While quantifying aberration of starlight, Bradley serendipitously stumbled across another unexplained apparent motion to the fixed stars, which kept him carefully observing. In 1748, he announced a further discovery: a nutation, or nodding motion, to the well-known larger motion of precession. Both precession and nutation originate from the gravitational pull of the sun and moon on the equatorial bulge of the earth. The spinning earth is not a precision gyroscope. Its rotational axis points not in one fixed direction, but over 26,000 years sweeps out an enormous circle, inexorably changing the direction of astronomical north (no, Virginia, Polaris has not always been, nor will forever be, our North Star). Precession is an effect large enough that it was discovered by the naked-eye ancient Greek astronomer Hipparchus two millennia before Bradley. It systematically moves every star one way on the celestial sphere by an amount and direction that depends on the star's position, ranging up to a maximum of 50 arcsecs per year.

What Bradley had additionally discovered was an oscillation to precession: the earth's rotational axis actually precesses in a rickrack wiggle with an amplitude of about 9 arcseconds and a period of about 18.6 years—traceable to the gravitational effect of the moon's orbital plane itself revolving once every 18.6 years [Fig. 3].

Despite the observational care of Bradley and instrumental skill of Graham, Bradley never detected any evidence of parallax for γ Draconis. Because of his confidence in the precision of Graham's zenith sector, Bradley concluded "it seems very probably that the parallax of it is not so great as one single second; and consequently that it is above 400000 times farther from us than the sun." (Bradley's lower bound, equivalent to six light-years, was correct: γ Draconis has an annual parallax of just 0.022 arcsec, and is 147 light-years distant—nearly 9.7 million times farther than the sun.)

"Most Glorious Triumph"

What was needed was still better instrumentation, plus some assurance even absent parallax that a star an astronomer chose to observe was actually quite nearby.

By 1840, three astronomers in three different countries using three different instruments—and after subtracting out the effects of precession, nutation, and aberration—independently and simultaneously measured annual parallaxes to three different nearby stars. They had all (wisely) picked their stars not because of their brightness, but because of their fast proper motions (movements across the line of sight), figuring that any stars clipping quickly across the sky must be nearby neighbors.

Friedrich Wilhelm Bessel—the same mathematician famous for Bessel functions—used a superb heliometer of 6.2 inches diameter at the Königsberg Observatory in East Prussia, built by the supreme instrument-maker Joseph von Fraunhofer of Munich (famous for discovering the dark absorption in the spectrum of sunlight that are still called Fraunhofer lines). The Königsberg heliometer was also known as a divided-lens micrometer: yes, first Fraunhofer figured a perfect lens—one quite large for the era—and then he had the courage to saw it in half so that one semicircular half-lens could be shifted with respect to the other to superimpose images of two stars in the field of view and precisely measure their angular separation.

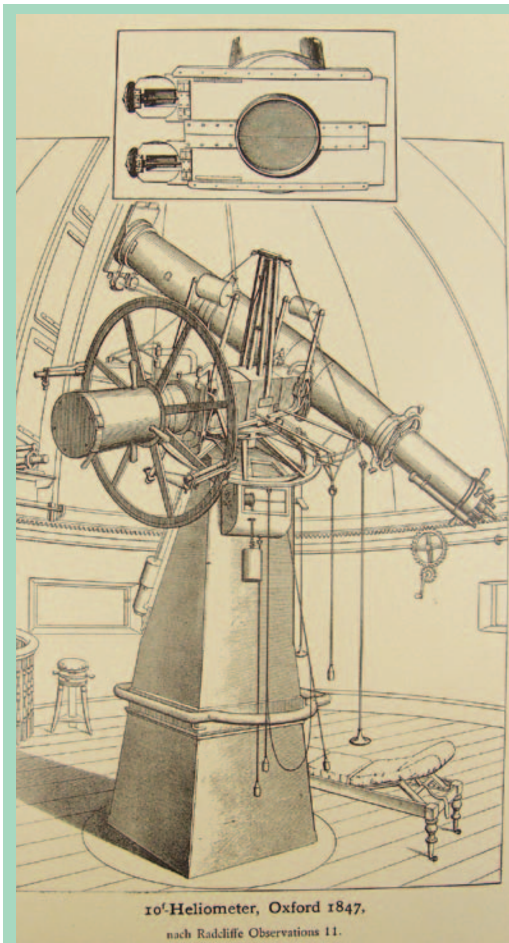

Fig. 4. The 7.5-inch heliometer at the Radcliffe Observatory at Oxford University, made by the Repsold brothers of Hamburg, was installed in 1848. Also called a divided-lens micrometer, its lens—like that of the Fraunhofer heliometer used by Friedrich Bessel at the Königsberg Observatory—was cut in half [inset at top], and one half slid away from the center of the other in order to measure small separations between celestial objects with great accuracy. [Credit: Joh. A. Repsold. *Zur Geschichte der Astronomischen Messwerkzeuge von 1830 bis 1900.* Leipzig: Verlag von Emmanuel Reinicke, 1914.]

Bessel's secret to success in measuring the parallax of his chosen star 61 Cygni (which has such a large proper motion—a whopping 5 arcsecs per year—that it was nicknamed the "Flying Star") was not just his care in the actual measurements. His success also lay in his extraordinary rigor in spending five full years—1829 to 1834—calibrating the optics, the mechanics, and the measuring scales, in all meteorological conditions, so as to document the behavior of the heliometer across the full range of possible observing conditions. Why? As wonderfully summarized by one nineteenth-century writer in *The North American Review,*

> When the astronomer undertakes to measure these minute angles, he finds Nature warring against him with all her powers. In the air above she never ceases to mix currents of hot and cold air, and thus keeps the telescopic image of every star in unceasing agitation,—like the image of the sun in a running stream. Expanding his instrument by heat, and contracting it by cold, she disarranges its most delicate adjustments, changes its form, twists its supports, and moves its microscopes. She blows a grain of sand under his spirit-level, and his observation is worthless. She will not even allow the most solid foundation of his instrument to rest immovable, but, alternately causing the ground beneath to swell with moisture and contract with drouth, keeps it in continual disturbance. ... The success with which the astronomer can carry on his battle depends on his foresight in anticipating Nature's attacks, and his ingenuity in devising means to thwart her.

In the early 19th Century, there evolved two approaches to building the best instruments of precision: the English style and the German style. Benjamin Apthorp Gould, the U.S. astronomer who founded *The Astronomical Journal,* which is still published, was one of half a dozen astronomers instrumental in bringing German methods to the United States. He observed that the English style was "designed for securing absolute uniformity of circumstances in all observations" whereas the German style was designed "for attaining as great diversity of circumstance as is consistent with retaining the same degree of accuracy." Put another way, the English style sought to attain precision by minimizing error, whereas the German style sought precision by recognizing that error was always present and ever changing, so the astronomer must constantly monitor and quantify error.

The German style was due in large part to Bessel's theory of instrumental errors, which effectively created a new art of observation. Defects that can be measured and allowed for are as good as nonexistent. In December 1838, after only a year of final visual observations, Bessel showed the power of this error-quantification approach: he announced that he had determined the parallax of 61 Cygni to be less than a third of an arcsecond (0.314 arcsec), implying its distance was 660,000 times farther than the Sun or about 10.4 light-years away. The modern value for 61 Cygni's parallax is 0.287 arcsec—within 10 percent of Bessel's initial measurement—placing the star 11.4 light-years from the earth. (Both sets of measurements from the other two observers were much less definitive than Bessel's.

In 1841, in awarding the gold medal of the Royal Astronomical Society to Bessel, Royal Astronomical Society president Sir John Herschel called the measurement of the distance to a star "the greatest and most glorious triumph which practical astronomy has ever witnessed."

Even today, such exotica as extrasolar planets around other stars in our own Milky Way galaxy, supermassive black holes in the center of the Milky Way and other galaxies, and the abundance of invisible dark matter throughout the universe are not discovered by being directly seen. Instead, their existence is inferred in part from the telltale patterns of movements of individual stars, masses of stars within galaxies, or entire galaxies. Spectroscopy, which can measure changes in position along the line of sight (the famous red or blue Doppler shifting of spectral lines for objects receding or approaching), is one essential tool in ascertaining motions, but is a latecomer to the party. The invention of spectroscopy is usually credited to Bunsen and Kirchoff in 1859. Only angular position measurement can detect changes in a celestial object's position across the line of sight—its proper motion.

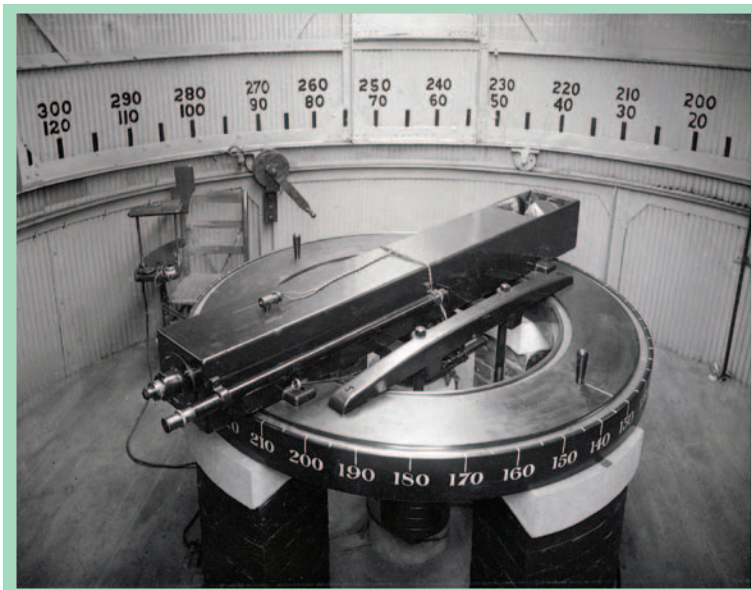

Fig. 5. Almucantar installed at Case School of Applied Science (now Case Western Reserve University) in 1900 is another instrument of precision looking very different from a traditional telescope. Like the original almucantar designed by Seth Carlo Chandler, it times rising or setting stars transiting (crossing) a fixed horizontal circle parallel to the horizon. The 6-inch telescope is the large rectangular box with an eyepiece at the left; light from a star is directed into the instrument by the angled flat mirror at its far end. Almost frictionlessly, the telescope rotates only in azimuth (instead of in altitude, like a meridian circle), as it rests on a heavy ring-shaped float in a trough of mercury. [Credit: Royal Astronomical Society, London.]

Hipparchus to Hipparcos

The precision of relatively small instruments allowed visual astronomers to detect such minute variations in the positions of stars that they actually identified changes in the earth itself. One famous example is that discovered by Seth Carlo Chandler, Jr., who measured latitudes and longitudes for a number of geodetic missions of the U.S. Coast Survey, and sought to design a latitude-finding instrument free of finicky adjustments to bubble levels. He designed a telescope to float on a mercury bearing that he called an almucantar [Fig. 5], whose 4-inch lens was built by American optician John Clacey and its mechanical parts by French instrument-maker G.F. Ballou. Chandler tested it for 50 nights in 1884 and 1885, making observations accurate to a few hundredths of an arcsecond—in so doing, discovering a complex wandering, wobbling motion of astronomical north with a period of about 14 months that could not be accounted for by instrumental or personal error. Such variation in latitude or polar motion is now recognized as being due to motions of fluid material in the earth's mantle.

The ultimate triumph of precise astronomical position-finding was the *Hipparcos* satellite, whose results are still being analyzed. By the late 20th Century, the limitations the moving earth and variable atmosphere and "warring Nature" put on astrometric measurements from ground-based instruments ultimately led to the European Space Agency's design of the **Hi**gh **P**recision **Par**allax **Co**llecting **S**atellite—named *Hipparcos* as a nod to Hipparchus, who discovered precession—to measure the positions and motions of stars from geostationary transfer orbit. Operated 1989–1993, its relatively small (11.4-inch or 29-cm) telescope determined the proper motions and parallaxes of more than 120,000 stars with a median accuracy of 0.001 arcsecond.

Folks, 0.001 arcsec is the angle subtended by 6.27 feet at the distance of the Moon—about the height of a suited astronaut. Let's hear it for the engineering of astronomical instrument-makers.

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