Wandering Pole, Wobbling Grid

Earth's rotation axis wobbles irregularly, changing the direction of true north, and varying latitudes and longitudes by 30 to 70 feet every year. The discovery of polar motion is a tale of instrumentation and serendipity.

By **Trudy E. Bell** (Text Copyright 2016 Trudy E. Bell)

The discovery of polar motion and its resultant variation of latitude is not only a tale of interdisciplinary and international cooperation enduring more than a century even through two world wars, but is also a classic example of serendipity.

NEWS FLASH: Earth's axis of rotation—whose orientation in space has determined astronomical true north since time immemorial—irregularly wanders each year in a veritable drunkard's-walk counter-clockwise spiral that varies from 30 to 70 feet across. Thus, the worldwide grid of latitude and longitude defined by astronomical north is also wobbling, with a magnitude about the size of an average residential house lot.

It was all Leonhard Euler's fault. In the 1750s, the Swiss mathematician became fascinated by the physics of spinning bodies. By the 1760s, he was wondering about the rotating Earth, recognizing that the planet is not a sphere and that its mass is lumpy with mountains and valleys. What would happen if its axis of figure (axis of its three-dimensional shape, passing through its center of mass) might not exactly coincide with its axis of rotation?

In 1765, he published a startling prediction: Earth's axis of rotation might migrate in a small circle around its axis of figure: that is, the direction of astronomical north might vary, causing an equivalent periodic variation in latitude of every place on the planet. Assuming a rigid Earth and calculating from the flattening of the poles, Euler predicted the latitude of every place might oscillate with a period of 10 months (305 or 306 days).[1]


Euler


Bessel

With astronomical instruments precise enough to determine a location's true zenith, such variation in latitude might even be detectable. Therein lay a catch: the angular amplitude of Earth's wobbling is minuscule—less than a second of arc, smaller than the angle of parallax of the closest stars when viewed from opposite sides of Earth's orbit around the Sun. Parallax itself posed such a monumental instrumental challenge that it was not detected until 1838, and even then was found only by precision visual observer Friedrich Wilhelm Bessel after he had devised his fundamental theory of instrumental errors and commissioned a special-purpose instrument (the heliometer) up to the task.[3,9]

Still, as instrumental precision improved over the 19th Century, half a dozen astronomers came close to stumbling across observational evidence for variation of latitude. Bessel himself suspected he might have detected some evidence for it in 1843 when he was testing a new meridian circle installed in the Königsberg Observatory, and noticed that his observations indicated the observatory's latitude might have changed since 1820. He also suspected something similar in a series of observations by his former student, positional astronomer C.H.F. Peters at Pulkovo Observatory in Russia. But he died before he could tell for sure.


Peters


Nyrén

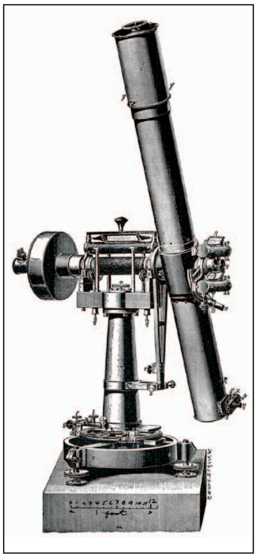
In the 1870s, Swedish astronomer Magnus Nyrén analyzed 375 observations of various circumpolar stars over two decades by different astronomers. He strongly suspected they showed evidence of polar motion but was puzzled why not at Euler's predicted period of 10 months. What was needed, he declared, was a continuous observing program to monitor latitudes to detect the true period and amplitude of any polar motion.[1]

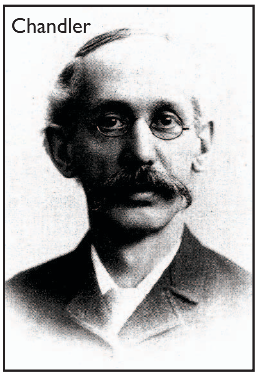
Then, two simultaneous sets of observations (1884–85) on opposite sides of the Atlantic burst wide the entire research field through pure happenstance.

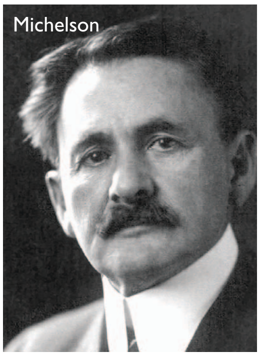
Seeking Worms, Striking Gold

First, in Cambridge, MA, Seth Carlo Chandler Jr., had just invented a brand new astronomical instrument he called an almucantar. From his early days with the U.S. Coast Survey in the 1860s (before the service added the word Geodetic to its name) using a visual zenith telescope to determine latitude, he had been annoyed that nearly half his time was spent squinting in dim light at finicky bubbles in precision spirit levels rather than observing stars in the night heavens. His almucantar was a self-leveling instrument floating on

BELOW: Instruments at the four main latitude observatories were identical Wanschaff visual zenith telescopes, having a lens diameter of 4.25 inches (108 mm) and a focal length of 51 inches (130 cm). An observer measured the angular distance of a star down from the zenith at the moment it crossed the meridian using spirit levels (two cylinders at far right); stars were observed in pairs, one crossing north of the zenith and the other south, and the telescope was rotated around the vertical axis between stars. *Credit: Report…U.S. Coast and Geodetic Survey [for 1899–1900], Appendix 5.*





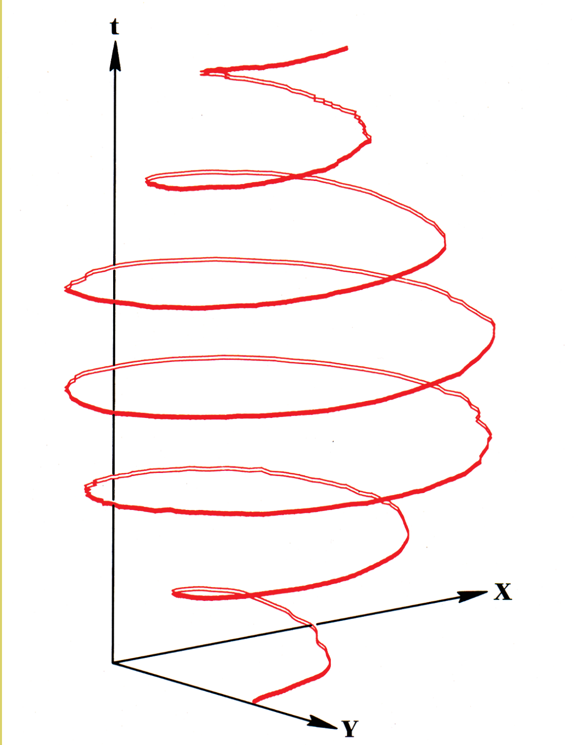


a bearing of liquid mercury, designed to be both easier and more time-efficient. From April 1884 to May 1885, Chandler rigorously tested his prototype by repeatedly determining the latitude of Harvard College Observatory, a well-known location. Although he kept finding discrepancies that could be explained only by a variation in the observatory's latitude, he thought it "too bold an inference to place upon record" when he published his analysis in 1887.[4, 6]

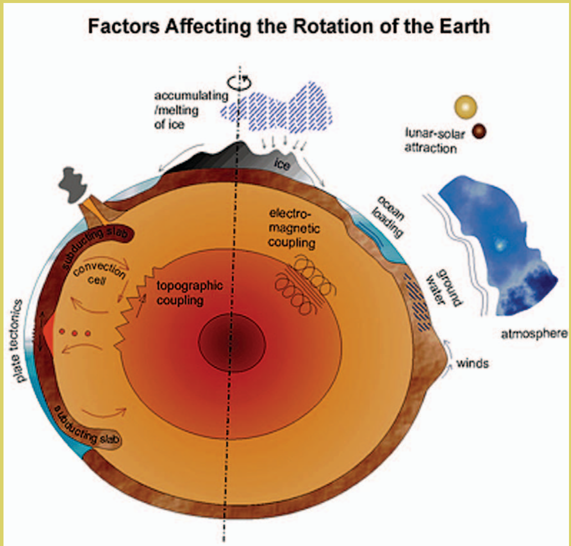
Meantime, recent measurements of the speed of light by U.S. physicist A.A. Michelson gave Karl Friedrich Küstner at the Berlin Observatory a realization: astronomers could more accurately determine the size of the solar system and other key cosmic distances if they could more precisely measure the aberration of starlight (the apparent angular displacement of stars in the heavens as the result of the Earth's orbiting the Sun[3]). So in 1884–85, Küstner began measuring that small angle with the observatory's new Bamberg universal transit instrument. But like Chandler, he found weird patterns in his data that could not be explained without allowing for periodic variations in the observatory's latitude—a conclusion he published in 1888.

Astronomers jumped on the announcement because variation of latitude (and for that matter, its concomitant variation of longitude[18]) would affect absolutely every fundamental measurement in celestial mechanics and positional astronomy, including star catalogs and precision timekeeping. Geodesists were equally electrified, because variation of latitude would affect every fundamental measurement in topographic mapping of Earth worldwide.

So in 1889, the International Geodetic Association (IGA) set up a special committee with funding to send observers to Hawaii, about 180 degrees of longitude



This three-dimensional plot of the irregular spiral motion of Earth's rotation axis shows how our planet's north pole wandered from September 1980 (bottom) through March 1988 (top). Horizontal axes x and y represent displacement in feet from Earth's axis of figure (in the spiral's center, not shown); time proceeds upward. Diameter of spiral ranges from about 30 to 70 feet; each spiral loop is about 14 months (the Chandler wobble). The time series spans rather longer than one cycle of the 6- to 7-year beat period of the Chandler wobble and a 12-month annual motion driven by meteorological effects. Small irregular variations in the polar motion are real disturbances, but not all physical causes are currently understood. *Credit: International Earth Rotation and Reference Systems Service*



Wobbles originate from numerous sources, including motions of matter within Earth's inner and outer core and mantle, earthquakes, volcanic eruptions, ocean currents and tides, winds, and freezing and melting of polar ice, as well as gravitational (land) tides from the Moon and Sun. Such forces also cause the Earth's spin to speed up or slow down by microseconds per day. For example, the 2004 magnitude 9.1 Sumatran earthquake is estimated to have shortened the length of day by 6.8 microseconds and shifted Earth's axis of figure by about 2.75 inches (7 cm). *Credit: U.S. Naval Observatory*

LEFT: The empty Gaithersburg latitude observatory, now a National Historic Site; the walkway commemorates all six observatories. The edge of the circular brickwork approximates the largest diameter of the pole's wandering. *Credit: Trudy E. Bell.* BELOW: Cincinnati Observatory director Jermain G. Porter beside one of the six observatories set up in 1899, with the zenith telescope visible. All were similar with a split roof (shown open). *Credit: Cincinnati Observatory Center*

latitude. However, they all showed "a revolution of the earth's pole in a period of 427 days, from west to east, with a radius of thirty feet, measured at the earth's surface"[7]—demonstrating a period 40% longer than Euler's prediction. Today, this primary period of about 14 months is called the Chandler wobble or the Chandler component.

That huge discrepancy nonplused astronomers and geodesists alike until Simon Newcomb—superintendent of the U.S. Nautical Almanac Office and a towering figure in 19th Century astronomy—reminded everyone that Euler had been assuming an "absolutely rigid" Earth. But fluid oceans cover part of the planet. Moreover, in a compelling thought experiment, Newcomb calculated that Earth likely was about as elastic as steel. He also cited geologists' observations that suggested Earth consisted of "a thin crust floating upon a liquid interior, and must therefore be a viscous solid."[16] Such sources of internal friction would lengthen the period.

The following November (1892), Chandler published another blockbuster paper, announcing, "The observed variation of latitude is the resultant curve arising from two periodic fluctuations superimposed upon each other." The first (and larger) was the 14-month wobble. The second had a 12-month (annual) period. The two beat against each other, their constructive and destructive interference causing both the amplitude and period of latitude variation to increase and decrease over about seven years[8, 14]—part of the reason why polar motion had been so difficult to detect.

That same fall (1892), when the observers returned from Hawaii and compared their measurements with those in Berlin and the United States, the preliminary results were clear. Latitude varied with a period significantly longer than Euler predicted, in counterphase on opposite sides of the planet: when the position of the Berlin observatory headed north, the observatories in Hawaii headed south, and vice versa; intermediate variations were recorded at San Francisco and Rockville.[19] (Visualize this by nodding your head: when your forehead tilts up, the back of your head tilts down, and your ears move less in between.)

away from the Berlin Observatory. The concept: set up a pilot latitude observatory for a year on the opposite side of the planet to compare its observations with another year of measurements at Berlin. The IGA also solicited the collaboration of the U.S. Coast and Geodetic Survey (USC&GS). It too deployed an astronomer to Hawaii; the Berlin and USC&GS astronomers built temporary latitude observatories about 30 feet apart at Waikiki (near Honolulu). As a further check on results, the USC&GS also set up temporary latitude stations in San Francisco, CA, and Rockville, MD, at longitudes and latitudes intermediate between Hawaii and Berlin.[19]

By mid-1891, all five observers were in position and training their visual zenith telescopes and other instruments at the heavens, accurately and repeatedly measuring their observing sites' latitudes.

The Chandler Wobble

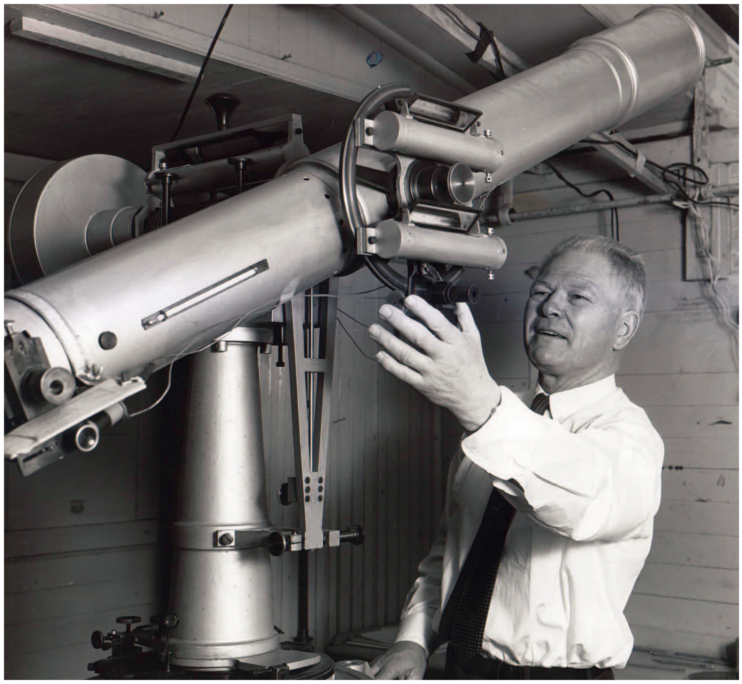
Meanwhile, as soon as Chandler saw Küstner's 1888 paper, he knew what he had measured at Harvard was real. After several years of intense mathematical analysis, Chandler published two seminal papers in November 1891. They showed that his almucantar results and Küstner's measurements were fully consistent with each other as well as with observations from Pulkovo, the U.S. Naval Observatory, and elsewhere, verifying the physical existence of the variation of

International Latitude Observatories

The idea for a concerted worldwide observing program to monitor and quantify polar motion was a proposal whose time had come. The ambitious goal: stand up four observing stations on the same parallel of latitude around the planet, and operate them for an initial campaign of five years.

The geodesists of the IGA knew that monitoring polar motion demanded skilled astronomers. So it opened negotiations with the Astronomische Gesellschaft, an international astronomical society founded in 1863, in part specifically to help orchestrate large worldwide research projects (the International Astronomical Union was not founded until 1919). Like all major multinational collaborative programs today, negotiations involved balancing competing national interests.

Alfred W. Helm adjusts the visual zenith telescope at the International Latitude Observatory in Gaithersburg, MD, where he was observer 1957–75, in this photo taken around 1960. The parallel horizontal cylinders above his hand are the spirit levels; mirrors helped the observer to read their precise graduations. The two eyepieces on the silver index ring read altitude to 0.2 second of arc. *Credit: Gaithersburg Community Museum*



One major influence was Japan, rocked in 1891 by the devastating magnitude 8.4 Nobi earthquake that killed 7,000. To minimize human cost of future earthquakes, the Japanese government immediately inaugurated major programs in geophysical research. As a nation just entering industrial development in the 1890s, Japan deeply wanted the prestige of one of the proposed latitude observing stations within its borders—manned by a native Japanese observer. Although the IGA agreed to that last condition reluctantly, true worldwide coverage demanded observations from Japan's longitude.

By 1898, after much international lobbying and wrangling, the parallel chosen was latitude 39° 8'. Four main International Latitude Observatories received full IGA funding for observatory construction, identical visual zenith telescopes, and support of an observer for five years: Mizusawa (then a rural town 300 miles north of Tokyo); Ukiah, CA, (115 miles north of San Francisco); Gaithersburg, MD, (just north of Washington, DC); and Carloforte, Italy, (on the island of San Pietro off Sardinia). Although not originally planned, Russian and U.S. astronomers enthusiastically volunteered two more locations: Tschardjui in Uzbekistan (to fill in a gap in longitude) and the Cincinnati Observatory (coincidentally already on the chosen latitude). Those fifth and sixth stations received partial funding and somewhat smaller zenith telescopes.

In 1899, the International Latitude Service (ILS) was officially born. All six latitude observatories were quickly built and instruments installed; by year end, all six observers had begun repeatedly and meticulously measuring their latitudes, using the same several dozen pairs of stars and the same observing protocols. The goal once their observations were combined: to monitor the x and y offsets of Earth's rotation axis as it spiraled around the axis of figure.

X, Y, Z

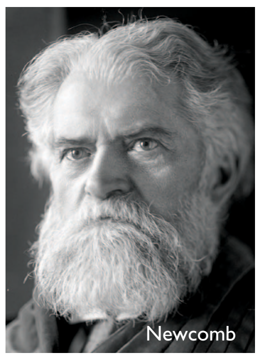
Within a year, something was clearly amiss. The measurements in Japan, made by 30-year-old Hisashi Kimura, seemed to have large errors compared with observations from the other five stations. The ILS Central Bureau assigned only half weight to the Mizusawa observations, called on Kimura to explain his methods, and requested an inspection of the instrument. A technical expert overhauled the zenith telescope. Still the discrepancies remained, seeming to follow an annual oscillation, as if each year Earth's center of gravity were slowly moving six feet up and down its axis of rotation.[2]

By 1903, it was clear that Kimura's observations were *more* exact than everyone else's, and that he had discovered a new non-polar phenomenon he dubbed the z term (in analogy to x and y) affecting all the stations. To study it further, both Chandler and Kimura independently called for additional latitude observatories in the southern hemisphere. In 1906, two were established in Bayswater, Australia, and Oncativo, Argentina, about 180 degrees apart at the latitude of -31° 55' and operated to 1908.[5,10]

By the 1960s, the z term was believed to be a response of Earth's fluid outer core to the tidal torque of the Sun—discovered by Kimura a decade before geologists observing seismic waves had even confirmed the existence of Earth's viscous core. Kimura received international acclaim and the z term came to be celebrated in Japan as the nation's first scientific discovery of world significance, even appearing in popular culture: Mizusawa was nicknamed "the city of z term," and Z was incorporated into the names of a school, a large city theater, and even a type of small pastry.[17]

Value Was Clear

When the initial five years were up, the outstanding value of the latitude observatories was clear to both geodesists and astronomers. The IGA renewed the worldwide observing program time and again, supplemented by independent measurements from scores of other observatories worldwide. Over the 20th Century, with multiple name changes, the International Latitude Service morphed into the International Polar Motion Service, and finally (2003) into today's **I**nternational **E**arth rotation and **R**eference systems **S**ervice (IERS)—becoming what former NASA chief historian Steven J. Dick calls "the longest-running series of focused observations in the history of astronomy."[1]



For the entire program, the International Latitude Observatories used visual observers and relatively small zenith telescopes, even after the advent of electronic technologies such as photographic zenith tubes, photoelectric astrolabes, and photoelectric transit instruments. But several game-changing technologies spelled the end of the visual program, shuttering the remaining five observatories in 1982.

One was Very Long Baseline Interferometry (VLBI), in which radio telescopes hundreds or thousands of miles apart observing quasars at the edge of the universe could monitor variation in latitude precisely enough even to track ongoing continental drift of Earth's tectonic plates. Others were lunar laser ranging and satellite laser ranging for more exact monitoring of earth dynamics. Still others were several satellite-based position-finding programs, notably the first constellation of ten satellites of the U.S. Air Force's Global Positioning System (GPS).

Today, with GPS and similar satellite constellations launched by other nations (collectively known as Global Navigation Satellite Systems), latitude and longitude are not referred to Earth's rotation axis. Instead, knowing the speed of the satellites' transmitted microwave signals in space and the atmosphere, a GPS/GNSS receiver instantaneously triangulates and calculates its 3D position from the arrival times of signals broadcast by whatever GNSS satellites are then above the local horizon. A minimum of four satellites within view of a handheld receiver is enough to determine geographical position to a precision of about 5 meters (16 feet); better receivers along with augmented measurements, procedures, and techniques can pinpoint locations to within centimeters.

Moreover, to account for variation of latitude and other variable characteristics, they specify position to a reference normalized to a standardized instantaneous moment in time and space; the most recent epoch, released in January, is called ITRF2014. (Specifying a positional grid according to a moment in time is the way astronomers map the ever-moving positions of stars on celestial charts, currently referred to epoch J2000, meaning January 1, 2000, in the astronomical convention of Julian years.)

Jolting the Planet

Quantifying polar motion has become precision science. Some 120,000 star positions were refined to 0.001 second of arc by the European Space Agency's Hipparcos satellite operating 1989 to 1993. Since the 1990s, a Doppler-based satellite tracking system called DORIS, for which satellite receivers monitor signals transmitted by ground stations, has proven its worth also in monitoring temporal changes in Earth's orientation, including polar motion. Yet for all the high tech, the original visual measurements remain the only long time record of Earth's polar motion we have, extending back to 1840. So they have been reanalyzed using sophisticated mathematical and computational techniques.[15]

Although the geophysical interpretation of Kimura's *z* term seems less certain today than it did in 1970, there is now no doubt that polar motion reveals information about the deep interior of planet Earth as well as changes in the oceans and air masses in the atmosphere. Indeed, other wobbles have been discovered having periods ranging from years or even decades down to under a day.

And finally getting more respect is Earth's comparatively overlooked axis of figure, around which spirals the rotation axis. Thanks to satellite techniques, the position of Earth's center of mass is now known to within a centimeter—the size of a dime—in three directions.[13] So now we can see that powerful earthquakes literally rock the planet: the 2011 magnitude 8.9 Fukushima quake jolted Earth's axis of figure 6.5 inches (17 cm) toward 133° E longitude.[11] "The change in the inner state of the Earth first brings about a variation in the figure axis, which then affects the polar motion," concluded geodesist Yoshio Kubo in 2012. "Therefore it is the variation of the figure axis on the Earth's surface but not the polar motion that geophysical events should be linked to."[12]

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Trudy E. Bell, M.A., (t.e.bell@ieee.org, www.trudyebell.com) has been fascinated with celestial mechanics since chasing grazing lunar occultations in high school. As an undergrad physics major, she was a lab tech for Lick Observatory's proper motion and parallax program; for *Scientific American,* articles she edited included ones on intercontinental baseline interferometry, astrolabes, and orbital theory. A former senior editor for *IEEE Spectrum* magazine, she now is a contributing editor for *Sky & Telescope* and a contract editor for the Union of Concerned Scientists.